Chapter 7
Synthesis for Management

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7.1 Introduction

In the foreword to Tom Andersen's "environmental history" of Long Island Sound (LIS), *This Fine Piece of Water* (Andersen 2002), Robert F. Kennedy, Jr., describes "a region of mythical productivity" observed by the first explorers.

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> They smelled aromas from Long Island's flowers before sighting land and found four hundred bird species, many of which are gone today. Henry Hudson's lieutenant Robert Juett described rivers choked with salmon (probably striped bass) and mullet. Giant dolphin pods schooled in the East River and New York Harbor. F. Scott Fitzgerald, one of Long Island's most faithful chroniclers in recalling its legendary abundance, suggested that the Sound appeared to the first Dutch sailor as the "fresh green breast of the new world," compelling him to hold his breath in "an aesthetic contemplation he neither understood nor desired, face to face for the last time in history with something commensurate with his capacity for wonder."

This bounty of Nature provided an ample supply of resources long before the complications of human use and consequent competition over ecosystem services became mainstream social and economic concerns. Ironically, the geographic construct of LIS and its watershed provided both abundant resources and ideal conditions for their exploitation from human habitation. Lewis (Chap. 2, in this volume) describes the geologic processes that molded the landscape and influenced the early patterns of human development along the Sound's shoreline and major river valleys. Weigold and Pillsbury's (Chap. 1, in this volume) history of land use surrounding LIS is also a history of the pollution and habitat loss that followed as a consequence. They describe how the "taming" of the land by settlers altered the geologic blueprint described by Lewis (Chap. 2, in this volume), reshaping the landscape to fuel the needs and desires of society. The use of LIS as a "nautical highway" (Weigold and Pillsbury, Chap. 1, in this volume) provided the means for trade and ultimately drew commerce from Boston to New York City and satellite harbors along the Connecticut coast.

The settlement and development of the coastline and watershed was a societal success story of human opportunity and adaptation; it also gave rise to pollution from agriculture, industry, and the effluvia of human populations. The urbanization of the Sound's watershed (Fig. 7.1), initiated in the nineteenth century, expanded quickly in the twentieth century. This was made possible by improved transportation systems and a growing middle-class population that was supplanted in urban centers, particularly New York City, by mass immigrations from Europe. At the western border of LIS evolved the world center of commerce, New York City, whose associated economic and social developments ultimately sprawled eastward along the Westchester County, Long Island, and Connecticut shorelines.

The sobriquets applied to LIS follow this theme, emphasizing human habitation as inherent to its character: The American Mediterranean according to Daniel Webster, *The Urban Sea* (Koppelman et al. 1976), and more recently, in the words of Prof. Glenn Lopez of Stony Brook University, "the first 21st century estuary." This last nickname suggests a broader narrative—a trajectory of change being duplicated in estuaries throughout the country: from natural paradise of plenty to natural resource extraction, the felling of forests for agriculture to industrialization, suburbanization, and, with the environmental movement, regulation and restoration. But the conclusion is not foregone. Today, new threats beckon—climate change, invasive species, emerging contaminants—while the old adversaries of habitat loss and nutrient pollution stubbornly remain.

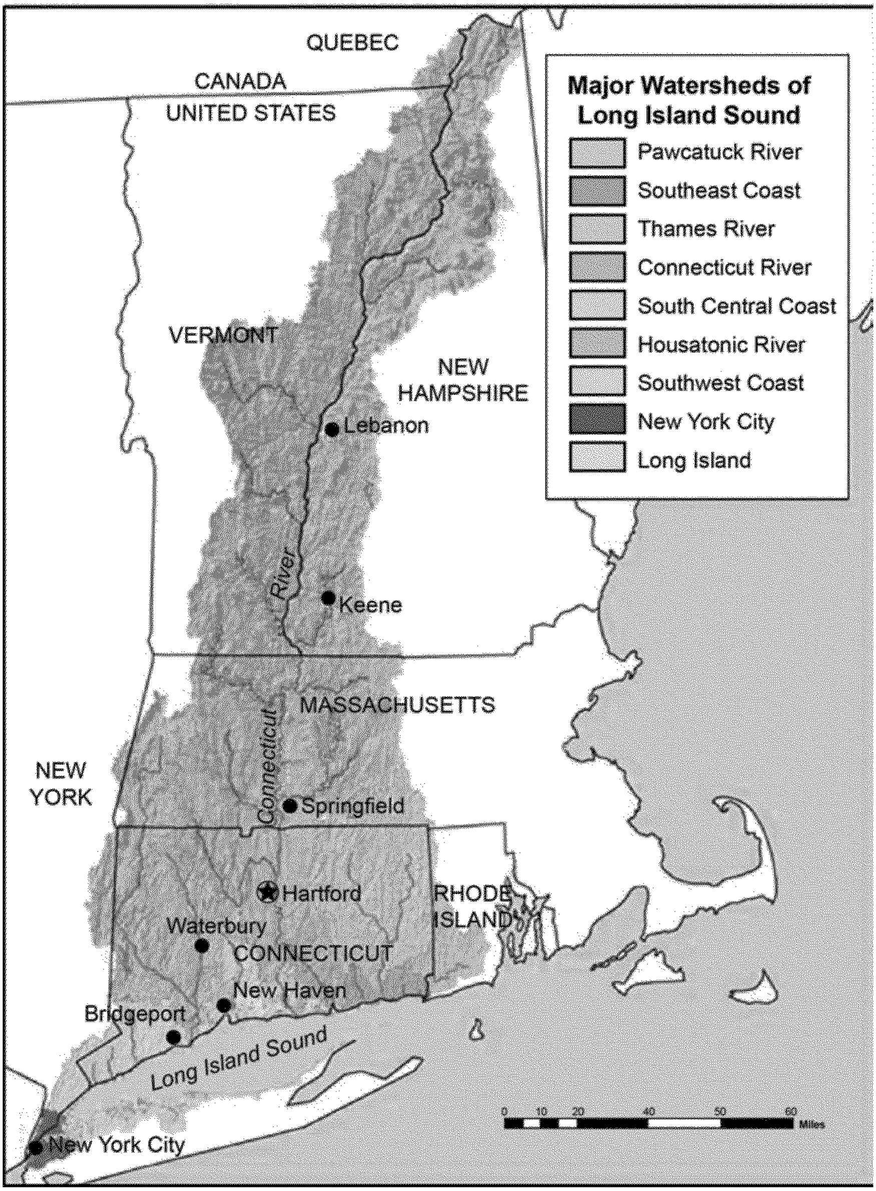

Fig. 7.1 The major watersheds draining to Long Island Sound

How this narrative concludes should matter to anyone concerned with our coastal environment. Long Island Sound is a harbinger of the fate of coastal waters and economies everywhere. Through all its changes, LIS, ever resilient, remains productive, providing leisure and livelihood. Lessons learned from efforts to understand and restore the LIS ecosystem are transferable to other coastal ecosystems and economies. For while the historical transitions observed in other estuaries may have started after or lagged behind LIS, the twenty-first century beckons for all.

This chapter begins with a brief review of the development of scientificknowledge in and around LIS. We then highlight some of the insights into the function of the LIS ecosystem that are described in detail in the preceding chapters, examine their linkages, and propose a set of actions to improve management of LIS. To accomplish this, it is essential to recognize the link between the health of the watershed and the health of LIS. This relationship is complex, especially in the densely-populated watersheds of LIS. Natural ecosystems are in a continual state of fluctuation,and our activities have accelerated the pace of change—physically, chemically, and biologically. Particular emphasis is placed on changes that may be driven by broader climate patterns and on the implications of such insights to the ecosystem and to regulatory and management approaches. Our hope is not to provide a definitivesynthesis for management, but to foster continued dialogue among scientists, environmental managers, economists, and the LIS community on actions needed to provide for a resilient and healthy ecosystem for generations to come.

7.2 ScienceFoundations

Perhaps the firstuse of "Long Island Sound" on a map was by Robert Ryder in 1670 (on filein the New YorkHistorical Society, February 2012). This may also be the firstmap of an "extensive area of colonial America" created using surveying instruments and techniques (Allen 1997). Only the western end of the map remains, but two-thirds of LIS is depicted and "Long Island Sound" is clearly labeled at the map's right edge. The scale of the Sound shoreline appears to be reasonably accurate, and many of the place names familiar today are identified including Eatons Neck, Huntington, Norwalk, Stamford, and Hell Gate.

Safe navigation to promote commerce was the impetus for the firstsystematic studies of the Sound. Long Island Sound was a relatively protected route to New York City and became increasingly important in the early nineteenth century despite the requirement to navigate the dangerous waters of Hell Gate. Steam power had allowed vessels to increase speed as well as tonnage, and thus vessel drafts became deeper. But the controlling depth for vessels entering New York Harbor from the Atlantic Ocean was about 7.3 m in the vicinity of the Sandy Hook, NJ to Rockaway, NY transect (Swanson et al. 1982; Klawonn 1977). Since ocean dredging was not yet technically feasible, and dredging a channel at Sandy Hook did not commence until 1885 (Klawonn 1977), entering New York Harbor through Hell Gate became a more desirable route. Still, as late as the 1840s, Charles Dickens, on a trip to the US observed, "The Sound, which has to be crossed on this passage, is not always a very safe or pleasant navigation, and has been the scene of some unfortunate accidents" (Dickens 1985).

Edmund Marsh Blunt and his sons published several maps of Long Island and its waters in the early 1800s, culminating in an 1830 chart of its north shore (Sound-side) that Allen (1997) judges as "relatively large scale" and "accurately done." President Thomas Jefferson created what was to become the Coast Survey (later the Coast and Geodetic Survey {C&GS} and now part of NOAA) in 1807. However, it was not able to undertake its mission until much later because of the War of 1812 and lack of Congressional support (Allen 1997). According to Allen (1997), Long Island and the surrounding waters were chosen as the location of the survey's earliest work because of Long Island's proximity to New York Harbor and the tortuous waters throughout the area.

These earliest surveys provide our first glimpses into the geomorphology and tidal phenomena of the Sound. They even afford some insight concerning the sediment characteristics of the waterways, as that was important information for secure anchoring. The surveys are designated as topographic and hydrographic. Topographic surveys are of the terrestrial land masses; hydrographic surveys are of the sea floor. The Coast Survey's topographic survey from Norwalk to Fairfield, CT was completed in 1835 at a scale of 1:10,000 (US Coast and Geodetic Survey Undated-c). Topographic surveys in the vicinity of Throgs Neck were completed in 1837, also at a scale of 1:10,000 (US Coast and Geodetic Survey Undated-c). Hydrographic surveys, completed at a scale of 1:10,000, covered the Sound floor from Flushing to New Rochelle, NY by 1837. The Race was charted by 1839 at 1:20,000. Both types of surveys were then published as maps or nautical charts at a smaller scale (US Coast and Geodetic Survey Undated-a, b). Initial hydrographic surveys of most of the Sound were completed by the 1840s. Sounding poles and lead lines were the depth measuring devices until the World War I era when the use of the velocity of sound in sea water became the preferred technique to measure depth (Shalowitz 1964).

The Battery, at the southern tip of Manhattan Island in New York City, is the site of the second longest time series of tidal observations (1856 to present) in the US. These data are commonly used to compare recent sea level changes on the East Coast. The earliest tide observations in LIS were made at Bridgeport and Black Rock Harbors, CT in 1835, followed by City Island and Throgs Neck, NY in 1837. These early observations contributed to the Coast Survey's first published government tide tables in 1853 (Marmer 1926).

Surface tidal current observations commenced in the 1840s (Stratford Shoals, Execution Rocks, Hart Island, and Stepping Stones) using floats and log lines. To the east, early measurements using floats were made near Plum Island, Cornfield Point, and the Thames River mouth. The first mechanical metered measurements were taken in the 1890s. The C&GS in 1934 released the first edition of *Tidal Current Charts, Long Island Sound and Block Island Sound*. From 1965 to 1967, the C&GS R/V MARMER resurveyed the tidal currents of LIS and Block Island Sound (BIS) at about 160 locations. These data, collected by the instruments of the day, were used to modernize and amplify the published tidal current tables and charts (Conover 1966).

Temperature (T) and salinity (S) measurements were recorded at the locations of C&GS current measuring stations dating back to the summers of 1929 and 1930. At that time, observations were obtained at some 70 locations from The Race to Hell Gate, including some in the Thames and Connecticut Rivers. Le Lacheur and Sammons (1932) summarized these data going back nearly a century in *Tides and Currents in Long Island and Block Island Sounds*. The authors also discussed tidal theory as it related to LIS, including that the tidal wave form was a combination of a standing and a progressive wave, and that Coriolis affected the tidal ranges on the north side of the Sound relative to the south side.

In the mid-nineteenth century, the geologic conditions that created Long Island were not yet understood. It was in the 1840s that Dr. Louis Agassiz's theories of glaciation were beginning to be published and accepted (Gilluly et al. 1959). Benjamin Thompson (1849), perhaps the preeminent natural scientist of his time in the area and a Setauket, NY resident, believed that the Island was "reclaimed from the sea," that is, it essentially washed up from the ocean floor.As explained by Lewis (Chap. 2, in this volume), it wasn't until the studies of Dana (1870, 1890) that Veatch (1906) and Fuller (1914) were able to describe the fluvialprocesses that created the Sound and establish that Long Island was, in fact, the residue of the Pleistocene ice advances and retreats. Fuller's (1914) *The Geology of Long Island* is a particularly important early study.

Weigold and Pillsbury (Chap. 1, in this volume) elucidate the importance of LIS's fisheryresources dating back to the colonial period. It is evident from this analysis that scientificstudies did not drive the early understanding of harvest effects as much as observations of reduced resources and implementation of trial and error policy actions to remediate stock declines. In fact, most of the problems that confront fisheries today were experienced more than a century ago. Overharvesting, unintended by-catch mortality, pollution, and public health were issues then, as were hindered migration routes for such species as salmon, shad, and alewives by construction of dams and spillways. And, as is true today, there were conflictsbetween commercial and recreational fishers on access and harvest rights.

A significantboost to better understanding the plight of living marine resources was provided by the establishment of the US Fish Commission by the Congress in 1871. For example, the 1895 *Bulletin of the Commission* reports on the status of the Atlantic menhaden (*Brevoortia tyrannus*) fisheryas well as food fishesin much of the northeast, including LIS, based upon surveys of the previous year. Today, the National Marine Fisheries Service (NMFS) is a descendant of the original commission, specificallyfocused on marine waters and their fisheries.Currently, the only federal marine laboratory on the Sound is the NMFS lab at Milford, CT, established there in 1931, with a focus on aquaculture, specificallybivalve shellfish.From ongoing measurements in Milford Harbor, the laboratory has T data since 1948 and S data since 1953. More recently, regional fishcommissions were established in 1942 (Atlantic States Marine Fisheries Commission) and in 1976 under the Magnuson-Stevens Fishery Conservation and Management Act (the New England Fishery Management Council and the Mid-Atlantic Marine Fishery Council) in order to understand and address regional fisheries that crossed jurisdictional boundaries.

Just as the federal government dedicated resources to investigate the condition of the states' fisheriesresources, so too did state governments. New Yorkand

Connecticut both established fishcommissions in the 1860s to examine the conditions of their fresh- and saltwater fisheries.Of particular concern to both was improving the deteriorating eastern oyster (*Crassostrea virginica*) beds in the western part of LIS. State commission reports document the changing conditions of the fisheries and the Sound in the late nineteenth century.

The oldest continuous water quality monitoring program in the US, which commenced in 1909, is New YorkCity's Harbor Survey Program. Originally established in response to public outcry about fouled waterways, the program has provided a rich database of unparalleled value to researchers and managers in the New York City region. The length of the data sets provides a unique view of how the water quality of New YorkHarbor and the westernmost parts of the Sound has changed over the years. Even during the program's earliest days, low dissolved oxygen concentrations were a problem in harbor waters. It is perhaps the firstrecorded instance for the marine environment of the US that the issues we now identify as hypoxia and anoxia were identified, significant problems that persist today (NYCDEP 2010).

The Bingham Oceanographic Laboratory at Yale University (1930–1966) conducted, documented, and synthesized some of the most important research concerning the physics, chemistry, and biology of LIS undertaken until the advent of the USEPA Long Island Sound Study (LISS). The work of that institution continues to provide a foundation for our understanding of many of the processes that define and impact the Sound today. In fact, the important reviews by Parker and O'Reilly (1991) and Capriulo et al. (2002) use the laboratory's studies as the basis for analysis. Gordon Riley and colleagues conducted a number of cruises in LIS and BIS in 1946, and his article about the hydrography of LIS (Riley 1952) was the most comprehensive synthesis of the physical oceanography of the Sound in its time, reviewing non-tidal currents, conservation of mass and salt, and lateral diffusion.

Predating the hydrographic work, Riley (1941) and the Bingham Oceanographic Laboratory initiated some of the earliest, if not the earliest, plankton studies of LIS. These studies were expanded upon in the 1950s and summarized by Riley and Conover (1967) in a volume of the *Bulletin of the Bingham Oceanographic Collection*. This volume contained a number of important papers. Richards and Riley (1967) introduced their studies of epifauna. Riley (1967a, b) mathematically modeled nitrate and phosphate in coastal waters, and, building on the work of Harris (1959), provided an early review of nutrients and nutrient cycling in the LIS ecosystem that has important theoretical and quantitative value today. Riley (1967a, b) also returned to physical oceanography with a paper on transport and mixing. Richards (1963) devoted an entire volume to the demersal fishesof LIS and continued to be actively involved in LIS research into the first years of the LISS.

These efforts served as a backbone of one of the firstsyntheses of the oceanography and environmental condition of LIS, published as *The Urban Sea* (Koppelman et al. 1976). More recently, with the rapidly escalating national and global interest in nutrient management, the early works of Riley and others provide one of the very few windows into the past through which resource and management goals can be viewed. Despite this trove of research, and spatially limited work by some programs such as the New York City Harbor Survey Program, it was not until 1985 with the advent of the LISS that concerted and intensive water quality research and monitoring efforts began in earnest.

7.3 Physical and Biogeochemical Setting

Long Island Sound is functionally an estuary, generally defined as "…semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage" (Cameron and Pritchard 1963). While the Sound is an estuary, it is an unusual estuary. It has entrances connecting to the ocean near its head (the East River) and its mouth (The Race). Physical oceanographers consider Hell Gate as the head, as it is there that stratification breaks down and the water column becomes well mixed due to turbulence (Fig. 7.2). The Connecticut River, which contributes 75 % of the gauged freshwater flow into LIS (O'Donnell et al. Chap. 3, in this volume), discharges along the Sound's northern flank but only a short distance from its mouth (about 15 % up estuary from its mouth to its head). The East River is not a river but rather a hydraulic strait in which the flow is controlled by a mismatch in the tidal phase and the tidal range at either end (Bowman 1976; Swanson et al. 1982).

The unusual character of the Sound is further defined by the long-term flux of salt, which is from the Sound toward New York Harbor (i.e., upstream and out of the estuary, contrary to typical estuarine patterns), as is the net flux of water. More consistent with what one normally thinks about an estuary, the flux of fresh water is from New York Harbor into the Sound (Blumberg and Pritchard 1997). As

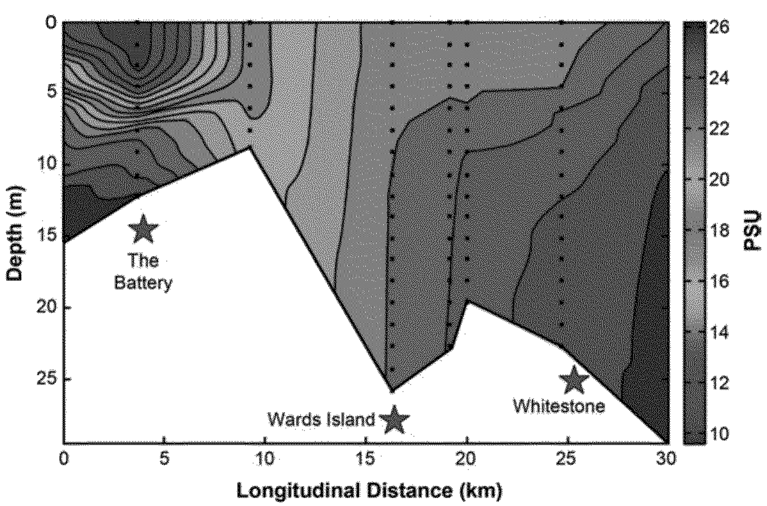

Fig. 7.2 Salinity section from Upper Bay of New York Harbor through the East River to Willets Point collected during the US C&GS MARMER survey of New York Harbor in 1959 (provided by R. Wilson). The Battery is located at the southern tip of Manhattan and Wards Island is near Hell Gate

pointed out by O'Donnell et al. (Chap. 3, in this volume), historical changes in the basin, such as engineering projects to improve navigation safety in the East River and the increase in the discharge of treated sewage into the East River, now on the order of 3.8 billion liters per day, have modifiedwater properties, decreasing S in western Long Island Sound (WLIS) and increasing exchange between the Sound and the East River, as confirmed in core studies by Varekamp et al. (2010).

As discussed in O'Donnell et al. (Chap. 3, in this volume), the unique aspects of salt transport within LIS make it difficultto classify according to an estuarine scheme proposed by Hansen and Rattray (1966) that considers only the relative contributions of advective and diffusive mechanisms. Crowley (2005) found that the westward salt fluxin LIS associated with the Stokes transport (mass movement in direction of wave propagation from oscillatory flows)was a dominant contributor to the total westward salt flux,and that the contribution from estuarine gravitational circulation was significantbut not dominant. Nonetheless, it is enlightening to use contemporary results to place LIS in the Hansen and Rattray classification. Based on the analysis of S and non-tidal velocity sections by Crowley (2005), and her analysis of the relative contributions of advective and dispersive mechanisms for salt transport, LIS can be classifiedas a Type 2 (partially mixed) estuary. It is influencedby Coriolis in which gravitational circulation makes a significant contribution to the upstream salt flux. As a comparison, both Chesapeake Bay and Narragansett Bay are partially mixed (Knauss 1997), while the entrance to Delaware Bay is considered to be vertically homogeneous (Williams 1962).

Long Island Sound also does not fitwell into the standard geological classifications of an estuary. It is neither a coastal plain estuary (drowned river valley) nor a fjord. Like its sister sounds along the southern New England coast (Fishers Island, Block Island, Rhode Island, Martha's Vineyard and Nantucket), it was shaped by streams and glaciers and became a marine system as sea level rose. Long Island Sound also has a feature that oceanographers would consider to be acting like a "sill" close to its mouth. However, according to Lewis (Chap. 2, in this volume), the "sill" developed after marine waters entered the Sound and does not fitthe geologic definitionof a structural (typically bedrock) ridge separating basins. It developed as glacial deposits in the easternmost Sound were eroded more than their western counterparts. The sill sits high above the underlying bedrock, has glacial Lake Connecticut deposits under it, and it is slowly migrating westward (Fenster et al. 2006) as marine erosion continues to reshape the basin.

Lewis (Chap. 2, in this volume) describes the recent advances in our understanding of the forces shaping LIS, laying out the geologic framework of the ecosystem, while noting that there remains some ambiguity concerning the nature and timing of marine transgressions into the Sound. The flanksof the Sound are geologically dissimilar. The northern shore consists largely of crystalline rock, while the southern shore consists of more permeable glacial deposits from which there is minimal surface runoff. Groundwater seepage is most likely the greatest source of fresh water to LIS from Long Island. Thus, dissimilar morphological and topographical features of the lands bordering the Sound play an important role in its physical oceanographic processes. The thalweg (the deep channel of a watercourse) is parallel to the mainland (coastal Connecticut), atypical of estuaries other than lagoonal systems. Most US estuaries incise a coast; LIS does not.

Lewis (Chap. 2, in this volume) states that the average depth of the Sound is 20 m, which is greater than the other major estuaries on the US East Coast. Because of this depth, LIS has not been dredged for navigation along its length, also unique for major US Atlantic Coast estuaries. Long Island Sound demarks a change from the sediment-dominated Atlantic coastline that extends southward to Florida from the south shore of Long Island to the largely bedrock-dominated shorelines northward of Rhode Island (with the exception of Cape Cod and some parts of Rhode Island dominated by glacial deposits). Interestingly, based on data from Ranheim and Bokuniewicz (1991), LIS appears to have only a weak turbidity maximum (around Cable and Anchor Reef), unlike the strong maximums experienced in Chesapeake Bay and the Hudson-Raritan Estuary. This may be partly a consequence of the relatively small flux of fresh water at the head of the LIS estuary.

The size and shape of LIS are such that it is a co-oscillating tidal basin with a frequency close to that of the semidiurnal tide. There is amplificationof the tidal range from its mouth to its head. The minimum mean tidal range occurs at The Race (0.7 m) and the maximum in the vicinity of Throgs Neck (2.2 m). The effect of Coriolis produces a slightly greater tidal range on the north side of the Sound than on the south side. High water occurs only about 2 h later at Throgs Neck than at The Race (a distance of 106 km). The corresponding tidal currents reach their maximum near The Race (approximately 2.6 m/s) and minimum near Throgs Neck, just to the east of the East River tidal strait where the hydraulic current, reversing at tidal frequency, is again swift (maximum approximately 2.6 m/s).

Long Island Sound experiences one of the largest intra-annual T ranges for estuaries throughout the world—28 °C (roughly between −1 °and 27 °C). Albion (1939) asserted that during the early days of steamboats "service was generally suspended" in the western end of the Sound "from mid-November to mid-March" because of ice. The Sound has frozen over on occasion in the recent past. The last such occurrence was January into February 1977 (US Coast Guard 2006), during a period of winters so cold some wondered if we were entering the next "little ice age" (Gwynne 1975). The US Coast Guard (2006) states that in 1977 "most of LIS was frozen over," and the "waters at Execution Rocks on the western end of the Sound were solid ice," measuring "2–3 feet thick in certain portions of the Sound."

The large T range, in conjunction with varying S (temporally and spatially), creates the seasons in the water column of the Sound. Typically, the water column is well mixed in winter. With spring and the freshening of the surface waters with lower density riverine water, S-driven density stratificationcommences. Shortly thereafter, solar heating drives the water column stratificationprocess as warmer surface waters are less dense than cooler, deeper waters. Wind mixing to depth all but stops, and dissolved oxygen (DO) drawdown begins. By fall, surface waters cool, autumnal storms enhance mixing, and the process begins anew.

Cuomo et al. (Chap. 4, in this volume) highlight how sediment geochemistry patterns reflectthe specificgeological and physical characteristics of the major basins, as well as embayments and harbors. These geochemical processes influencethe sources, fate, and effects of chemical species, which in turn affect benthic organisms. Overall, the sub-tidal, fine-grainedsediments found in WLIS and in the majority of harbors and embayments are characterized by reducing conditions. A large amount of the organic carbon present in the sediments of WLIS undergoes anaerobic, microbially-mediated decomposition rather than aerobic decomposition, or direct consumption by benthos, which dominates in eastern Long Island Sound (ELIS). While aerobic decomposition or direct consumption by benthos also characterizes the sediments of central Long Island Sound (CLIS), this basin is transitional. Cuomo et al. (Chap. 4, in this volume), therefore, recommend that the sediment geochemistry of CLIS be closely monitored to detect trends in carbon deposition and shifts in the balance between aerobic and anaerobic decomposition. Trends in nutrient control and climate change may tug CLIS in opposing directions; sentinel monitoring may provide insight into how LIS responds more generally to these changes.

Cuomo et al. (Chap. 4, in this volume) also emphasize that remineralization of organic matter in the sediments of WLIS and, possibly, CLIS provides additional N to the bottom waters of the Sound. This source of N, however, is poorly constrained in present models and is not measured by ongoing monitoring programs. While Lopez et al. (Chap. 6, in this volume) demonstrate that most of the oxygen demand in LIS occurs in the water column, additional sediment nutrient rate measurements, both spatially and temporally, would help elucidate this balance.

The Sound's numerous embayments add to its complexity. Infrastructure (e.g., wastewater treatment facilities (WWTF), industries, transportation corridors, stormwater sewers), concentrated along bay and harbor shores, is a source for pollutants that can impact the Sound. Each embayment is a micro-system controlled by its own geomorphology and anthropogenic modifications.Some have narrow, tortuous entrances through baymouth bars; in other cases, embayment mouths have been hardened with breakwaters or jetties. Some have been deepened by dredging, altering the natural flushing.Placement of the dredged material in some instances has further changed flow characteristics.

Yet, despite their importance for recreation and commerce, the Sound's embayments are relatively understudied, and little is known about their interaction with the main basins. Do embayments transport pollutants into LIS or do geology and modificationsrestrict transport of water and sediment? Perhaps embayments are sinks for many sediment-bound pollutants, which get into the Sound only after they are dredged or during large storm events. This is particularly relevant to the issue of dredging because in WLIS and CLIS, tidal resuspension of sediment dominates net long-term influxof sediment to LIS from the watershed. Understanding the sources and deposition rates of sediments that need to be dredged to keep open recreational marinas or federal shipping channels would help target sediment management programs.

Another issue of management interest is the degree to which embayments cycle nutrients internally, mitigating impacts upon the greater Sound. Sea level rise may alter exchange between the Sound and the bays. For example, sea level rise may change flood-dominatedembayments to ebb-dominated or vice versa—conditions that were mechanically achieved, for better or worse ecologically, over the past century. Stony Brook Harbor, one of Long Island's most pristine bays, is strongly flood-dominated (Swanson and Wilson 2005). This harbor fills semi-daily with oxygen-rich surface waters from Smithtown Bay. Dredging of the entrance channel, which has never occurred, to 5 m would allow hypoxic bottom waters from Smithtown Bay to flowinto the harbor during summers (Swanson and Wilson 2005; Bauer 2012). Clarifying the functional relationships between these water bodies and the Sound would enhance the overall effectiveness of management.

7.4 Pollutant Sources, Conditions, and Management

7.4.1 Metals

Varekamp et al. (Chap. 5, in this volume) describe the changing landscape and human and industrial legacy using metal profiles captured in LIS sediments. Sediment depth profiles chronicle pollutant loads over time as they increased rapidly during the Industrial Revolution and decreased with the advent of stronger state regulations, changing economies and consumer demands, and eventually the federal Clean Water Act (CWA). In recent decades, pollutant sources shifted from industry to sewage and urban runoff, as heavy industry moved overseas and human populations around LIS grew.

As described in Chap. 5 (Varekamp et al., in this volume), metals distributions in sediments reflect the proximity of sources and parallel grain size and organic carbon distribution in LIS. In spatially comprehensive surveys of sediments (e.g., Mecray and Buchholtz ten Brink 2000), Ag, Cu, Cd, and Hg were found to be enriched in LIS sediments, and increased in concentration with proximity to New York City (Mitch and Anisfeld 2010). Sediments are finergrained and higher in organic carbon content toward New York City (Knebel et al. 2000), and metal concentrations generally exceed natural concentrations, sometimes by many times. Silver is highly enriched in some locations, which Sañudo-Wilhelmy and Flegal (1992) link to WWTF effluent. Varekamp et al. (2005) report Housatonic River sediments are invariably enriched in Cu, Zn, and Cr, and estimate that the level of enrichment from metal sources from that basin could explain up to 20 % of the Cr and Cu in many LIS sediment samples.

The coastal embayments of LIS that are characterized by low energy, depositional dynamics, and proximity to sources are enriched in metals relative to those sources (Breslin and Sanudo-Wilhelmy 1999). Because harvestable shellfish resources historically are located near many of the most urban harbors of LIS where their food sources are stimulated by nutrient inputs from major tributaries, O'Connor (1996) cautioned that metals in shellfish may be of public health and environmental concern.

Sediment core data, as reported in Chap. 5 (Varekamp et al. in this volume), provide a distinct historical record of change in metals concentrations in LIS sediments. Radioisotope-dated sediment cores show metal concentrations slowly increased as development and industry grew in the early to mid-1800s; accumulation rates increased with the growth of industry through 1980. Between 1980 and 2010, stricter water pollution laws helped abate metals discharges into LIS and its major tributaries, and heavy industry moved overseas; the sediment core record shows concomitant declines in metals.

Mercury (Hg) has a rich history as both a pollutant and as an intensively-researched case study. Mercury discharges were related to industries, especially the hat-making industry, and sewage. Interestingly, the sedimentary record shows the signal from wet periods when contaminated sediments washed from the watersheds to LIS created "peaks" in the record, particularly in the late 1800s and early 1900s, but also in the 1960s–1970s. Varekamp et al. (Chap. 5, in this volume) attribute 20–30 % of the Hg to hat making and up to 25 % to sewage, with the balance coming from sediments contributed by the Connecticut River and other tributaries from watershed sources, including atmospheric deposition.

Changing consumer demands and stronger environmental regulation were probably most responsible for lowering sediment burdens of metals including Hg. However, Hg remains a concern because of potential redistribution of legacy contaminants in the sediments and continuing inputs of atmospheric sources from burning of fossil fuels. Persistent fishtissue contamination with Hg throughout the Northeast is symptomatic of this problem. All the New England states and New York have consumption advisories for Hg, primarily in freshwater fishes(CTDEP et al. 2007). A 2007 Northeast Regional Mercury TMDL summarizes the many pollution prevention steps taken by all the participating states to control sources of mercury in recent years. Those actions virtually shut down active, waterborne sources associated with sewage, especially from dental amalgam, other medical and scientificuses, and general products with practicable alternatives (King et al. 2008; NEIWPCC et al. 2007). Despite the regional efforts to control Hg, windborne sources from outside the watershed are linked clearly by modeling and source studies (NESCAUM 2008) as the major contemporary contributors to Hg pollution in the Northeast (CTDEP et al. 2007).

7.4.2 OrganicContaminants

Varekamp et al. (Chap. 5, in this volume) identify the primary sources of organic contaminants to LIS: WWTFs, urban runoff, combined sewer overflows(CSOs), and atmospheric deposition. Unregulated sources originating from everyday products used in homes and yards and from transportation infrastructure and vehicle emissions, however, contribute contaminants to surface runoff and ground water. Clean Water Act requirements, especially permitting of industrial and increasingly stormwater sources, have reduced the inflowof toxic organic compounds (USEPA 2011a). Product bans, most notably persistent chlorinated pesticides and polychlorinated biphenyls (PCBs), have eliminated new sources, but legacy sources are still active. Many organic compounds are volatile, allowing global distribution to levels of concern in some cases. Riverine inputs, particularly in industrial and urban settings, extend the range of contaminant sources. Major waterways, especially navigable waters, have served as ports and sources of power that were ideal hosts for industrial activity and sites for waste disposal. Broad use and combustion of petroleum in various fractions for fuels, lubricants, and a multitude of carbon-based products have led to wide distribution of polycyclic aromatic hydrocarbons (PAHs) that often reside in fine sediments of harbors and waterways.

The sediment organic contaminant database reported by Varekamp et al. (Chap. 5, in this volume) is not as rich as the database for metals. From a comprehensive evaluation of organic contaminants begun in 1995 by the USGS, Varekamp et al. report generally higher levels of organic contaminants in WLIS, particularly for PAHs and PCBs, which share a similar distribution pattern (See Figs. 5.18 and 5.19 in Chap. 5, in this volume). The Mitch and Anisfeld (2010) data review also revealed a general increase in organic contaminants toward the western end of LIS, especially for PAHs and PCBs, but also for DDT.

High sediment concentrations of organic compounds were reported in some coastal embayments, especially New Haven Harbor (Varekamp et al., Chap. 5, in this volume). NOAA National Status & Trends Program data identify the Housatonic River, Mamaroneck Harbor, and Throgs Neck as areas of high (>85 % percentile of national levels) PCBs and PAHs. Mitch and Anisfeld (2010) found those same harbors to exceed the 85 % percentile for almost all pesticides in sediments, and Yang et al. (2007) further reported that pesticides had not consistently diminished in concentration in the past two decades. Despite these observations, the data were insufficient to detect significant differences between nearshore and open water sites for LIS. This may be due to sample distribution, especially because the preponderance of the USEPA National Coastal Assessment (NCA) sites, and thus analytical data, are from open waters of WLIS; no sediment core data similar to studies of Varekamp et al. (2005) for metals are available for organic contaminants.

Polychlorinated biphenyls are a continuing concern because they bioaccumulate in fish tissues, particularly larger, predatory species such as bluefish and striped bass (Varekamp et al., Chap. 5, in this volume). These migratory species can accumulate PCBs from sources throughout their range, particularly the Hudson River and LIS. As a result, Connecticut and New York have issued consumption advisories for those species taken from LIS, although their respective advisories vary as a result of different interpretations of health risk. Both states continue to remediate active sources of PCBs and act to minimize redistribution of contaminated sediments dredged from harbors. Nevertheless, the pool of PCBs in LIS and regional locations that contributes to tissue contamination is still large enough to be of concern for human health. A recent survey of fish tissues from target species in LIS, including bluefish and striped bass, however, shows reductions in the levels of PCBs in both species (Skinner et al. 2009). As PCBs no longer are manufactured in the United States, burial and decay of PCBs are expected to result in a continuation of the downward trend.

7.4.3 Toxicity of Contaminants in Sediments

The expansive list of trace metals and organic compounds has overwhelmed regulators' ability to test for toxic effects of individual pollutants. The USEPA has maintained a list of fewer than 130 "priority pollutants" that provide insight into classes of pollutants that are expected to be toxic to humans, fish,and wildlife if threshold concentrations and exposures are exceeded (Copeland 1993). However, hundreds of additional chemical compounds, both inorganic and organic, are regulated under the Resource Conservation and Recovery Act (RCRA) and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, commonly known as Superfund) as "toxic pollutants" in a risk-assessment framework (USEPA 2008; 2011b). The LISS has focused assessment and management primarily on legacy contaminants and contaminants that exceed levels of concern in sediments and/or tissues of living organisms, especially those that might be consumed by humans and present a public health risk, as described in Varekamp et al. (Chap. 5).

A few national surveys have been conducted that test sediment toxicity in LIS and several of its embayments, summarized by Varekamp et al. (Chap. 5, in this volume). Primary sources of data include the NOAA National Status & Trends (NS&T) Program (O'Connor et al. 2006; Kimbrough et al. 2009) and the USEPA NCA (USEPA 2004; 2007; 2012). While "effects response levels" for bulk chemical analyses have been used to determine potential toxic impact levels on ecosystems from sediment burdens (see Figs. 5.18 and 5.19 in Chap. 5, this volume), whole sediment bioassays are used more commonly to test general toxicity. These tests more realistically assess the toxic impacts on living organisms compared to effects response levels derived from bulk chemical analyses. Tests are conducted in a controlled laboratory setting and assess the effects of the "mix" of chemicals that may reside in complex depositional areas of LIS under ambient physical and chemical conditions directly on sensitive marine species (See Sect. 5.6.2, in this volume).

The earliest toxicity surveys of consequence were NOAA's NS&T studies, which employed a variety of organism sediment assays in the main body of LIS and its embayments, reported by Wolfe et al. (1991). The use of an amphipod, *Ampelisca abdita*, under a 10-day exposure regime provided a relative indication of toxicity from surveyed sites. In general, embayments yielded the highest level of toxicity, with 80 % of those sites exhibiting sediment toxicity (see Fig. 5.26 in Chap. 5, in this volume); open water LIS sediments showed relatively little toxicity. More recently (2000–2006), work using *A. abdita* tests in the USEPA NCA showed that sediment toxicity still persists in many embayments, though there are indications that levels of toxicity are declining compared to earlier surveys (see Fig. 5.27 in Chap. 5, in this volume).

7.4.4 Nutrients

In many ways, nutrient enrichment has redefinedestuarine pollution biology and management for much of the nation in the last 30 years (Bricker et al. 1999, 2007). Long Island Sound is no exception, with the impacts of N enrichment garnering the majority of LISS research, monitoring, and management dollars. Seasonal hypoxia, a symptom of cultural eutrophication, has been the focus of research since surveys in the mid-1980s showed it to be a predominant problem (Welsh and Eller 1991; Parker and O'Reilly 1991) affecting large portions of WLIS and into CLIS each year (see Fig. 5.2a, Chap. 5, in this volume). Subsequent research and analysis has shown more expansive effects of nutrient enrichment, often interacting with other chemical, physical, and biological changes.

Nutrient fluxeshave been the subject of intensive monitoring and study to support the most effective mix of management options that would meet state water quality standards for DO. Nutrient inputs are variable over time and space and subject to differences in delivery efficiencyto LIS because of attenuation processes during riverine transport and in the Sound itself. Therefore, long-term monitoring data analyses conducted by the USGS and others reported in Chap. 5 (Varekamp et al. this volume) have been extremely valuable. Mullaney et al. (2002, 2009) reviewed N loads from major tributaries discharging into LIS from 1974 to 2008 to characterize nutrient loads and identify trends. Significantdownward trends in total N loading were observed at seven of 11 sites, with total loads from the seven sites falling from 21 to 15 Mkg/yr, more than a 25 % decline (see Table 5.9, Chap. 5, in this volume). Control of N from WWTFs in both Connecticut and New York has yielded substantial N reductions, with the discharge from both states combined falling from 31 to 22 Mkg/yr. The Chap. 5 analysis also shows the relationship between land cover and total N yields, which ranged from 3.0 kg/ha-yr in the least developed watersheds to 21.4 kg/ha-yr in watersheds with dense development and WWTFs contributing N.

Groundwater contributions of N can be a perplexing problem especially in the sandy, porous soils of Long Island, which lacks the major riverine delivery routes that exist to the north of LIS, and in some CT embayments (e.g., Niantic Bay). The concentrations of N in the groundwater aquifers of Long Island increased between 1987 and 2005 (Suffolk County 2010), mainly due to increased development and contributions from on-site wastewater treatment systems (e.g., cesspools and septic systems). This points out that, despite management efforts, continuing population increases contributing to nonpoint sources of N have increased loading. This concern is diminished somewhat by the relatively small area of the LIS watershed on Long Island, which contributes a total N load of less than 1 Mkg/yr (Scorca and Monti 2001)—less than 2 % of the total N load delivered to LIS by combined sources in Connecticut and New York (CTDEP and NYSDEC 2000). Although a relatively small load, it is still of management interest and subject to a load allocation to meet the TMDL requirements. It is also indicative of the challenge of N contributions from on-site wastewater treatment systems throughout the watershed. Varekampet al. (Chap. 5, in this volume) point out that further research is needed to understand the relative importance of groundwater sources of N, their origin (e.g., contributions of subsurface disposal compared to fertilizers), and the transport mechanisms in ground water, including travel times and attenuation from source to delivery to LIS and its embayments.

Chapter 5 also provides a brief look at the distribution of nutrients in the water column (Varekamp et al. in this volume) and its relationship to features of primary productivity in the Sound. A strong east–west gradient is apparent, with highest N concentrations in the far WLIS. Seasonal cycles also are readily apparent, as inorganic N builds during the fall and early winter, and then declines rapidly in late winter as the "spring" bloom of phytoplankton occurs, also apparent in chlorophyll *a* peaks at that time (Lopez et al., Chap. 6, in this volume). Generally, N becomes limiting after the spring bloom, and remains so during much of the summer. Research by Capriulo et al. (2002) and Gobler et al. (2006) supports N limitation observations and further demonstrate that NO_3/NH_3 ratios can determine dominant phytoplankton groups by preference for one N species over another.

In addition to the short-term trends, Varekamp et al. (Chap. 5, in this volume) evaluated the longer historic record of primary productivity in the Sound using sediment core data. Using organic carbon and N concentrations, organic carbon accumulation rates were estimated as a proxy for nutrient loading. The analysis was able to discern changes over time that could be related to landscape changes, such as deforestation as early as the 17th century, and primary productivity increases in LIS through about 1850. The picture becomes more complicated at that point (See Fig. 5.45, Chap. 5, in this volume). Productivity apparently decreased between 1850 and 1900, followed by an increase until 1950, then a decrease to the relatively low values of today. Recent sediment conditions reflectchanges in labile carbon from terrestrial sources versus marine carbon sources and changes in how nutrients from land runoff and WWTFs affect the levels and type of organic carbon generation.

7.4.5 PollutantManagement

With this complexity of cause and effect related to pollutant release into the environment, it is often difficultto identify problem pollutants and their interactions, and institute remedial actions before the damage is done. While nutrients are a natural and necessary ingredient in a healthy LIS ecosystem, enrichment of nutrient levels can alter community structure, favoring species adapted to those conditions. Legacy pollutants such as PCBs are a good example of the damage a single type of pollutant can cause. More difficultare some of the emerging contaminants discussed brieflyby Varekamp et al. (Chap. 5, in this volume). Polybrominated diethyl ethers (PBDEs), used as fireretardants in clothing and other everyday products, are persistent, accumulate in living tissues, and are known to have effects on living organisms, although the risk to humans is somewhat unclear. High levels were reported in mussel tissues in the LIS estuary (Varekamp et al. Chap. 5, in this volume). Because of structural similarities to PCBs, a known carcinogen, bans—sometimes for various forms—have been instituted in many nations.

Endocrine disrupting compounds (EDCs) have come under increased scrutiny for likely effects on estuarine fishesand invertebrates, particularly related to reproductive success of some species. A wide range of substances has potential to disrupt endocrine systems of organisms, with consequences including changes in sex ratios and general decline in population health and viability (Duffy et al.

2009; Laufer and Baclaski 2012). Broad classes of substances can act as EDCs and mimic hormones in estuarine organisms. These include pharmaceuticals, personal care products, detergents, pesticides, and even some metals.

Varekamp et al. (Chap. 5, in this volume) conclude their analysis with the summary statement, "Long Island Sound represents an estuarine system significantly impacted by anthropogenic activities." Although acknowledging that water quality has improved in the past 30 years following better regulation and management of pollutant sources, they note there still is cause for concern, especially with legacy pollutants, emerging pollutants of concern, nutrients, and climate change. They highlight nutrients as a "pervasive and disrupting" problem—one clearly associated with human presence, lifestyle, and economy, with cultural eutrophication showing few signs of improvement and at greater risk from a changing climate. Continued research and monitoring is needed to better understand and more effectively manage these issues. Nutrient and hypoxia monitoring should be continued with added attention to changes in pH, T, and system processes caused by climate change. Metals and organic compounds in sediments and the biota need to be monitored to track their fate and ensure that public health is protected while consuming seafood. Like nutrients, the dynamics of toxic pollutants may change, including release from sediments as T and pH vary. Finally, Varekamp et al. (Chap. 5, in this volume) call for monitoring plans and research to address emerging contaminants.

An important issue not treated within Chap. 5 is contamination of LIS by human pathogens, primarily from untreated or inadequately treated human sewage or from wild and domestic animal wastes. This is attributable to the fact that the obstacles to reducing pathogen impairments are not primarily related to gaps in estuarine science, and, therefore, generally have not been the focus of coastal research institutions. As described in the LISS's Comprehensive Conservation and Management Plan (1994), because of the public health implications to humans, management programs target source reductions to improve water quality, while minimizing human exposure through monitoring, bathing beach closures, and shellfishharvesting restrictions. Achieving source reductions requires continuing investments to abate CSOs, address failing on-site wastewater treatment systems, and control storm water. Recent successes include the completion in 2011 of a Sound-wide no-discharge zone for boater waste with the addition of portions of New York's waters to the Connecticut ban. Further recommendations for managing pathogens to LIS are included in the broader recommendations in Sect. 7.7.

7.5 Biology and Ecology

7.5.1 Historical and Current Conditions

Historic habitat loss and overfishingexert structural and functional changes in coastal ecosystems that reverberate into the present (Jackson et al. 2001). But understanding the extent of those changes and setting targets for protection and restoration of biological communities are often hindered by a lack of data on historical abundances and understanding of ecosystem processes. This certainly is true for LIS. Lopez et al. (Chap. 6, in this volume) note that the current extent of many habitats can be quantified, but what has been lost and how much of that loss can be recovered is largely unknown or undocumented. To some extent, ecosystems and environmental conditions can be reconstructed through core studies, but this is not an option for littoral communities and seaweeds, for which there has been little monitoring of species type, distribution, or abundance. It applies even to comparatively well-studied habitats such as tidal wetlands and seagrasses, which have been subject to regulation through legislation and have been targeted for restoration, or to well-studied sites, such as around power plants, that do not encompass the full suite of ecosystem components or stressors.

Tidal wetlands loss along the Connecticut coast estimated from 1880s Coast and Geodetic Surveys was 30 % prior to legislated protections (Dreyer and Niering 1995). Losses vary along the coast, with more than 60 % lost along the more densely developed western part of the Connecticut shoreline. Although no estimates exist for the loss of tidal wetlands along the entire Sound shoreline of New York, it is likely that similarly high losses occurred along the western portion. Tidal marshes that weren't filledor dredged were ditched for mosquito control, which altered hydrology and modifiedthe marsh plant and animal communities. The loss of seagrass communities has not been quantified,although it is clear from historic accounts that eelgrass (*Zostera marina*) was common throughout LIS prior to the 1931 die-off from a fungal infection referred to as wasting disease. Eelgrass recovery was limited to the eastern portions of LIS (see Fig. 6.7 in Chap. 6, in this volume). Comparing the habitat requirements of eelgrass with current water quality confirmsthat WLIS will not support eelgrass and that conditions in CLIS are marginal at best. Recent surveys supported by the LISS indicate that the majority of eelgrass is found east of Rocky Neck State Park in Connecticut and around Orient Point and Fishers Island in New York. Conducted in 2002, 2006, and 2009, these surveys need to be continued to document the spatial and temporal variability of eelgrass in LIS and to better understand responses to water quality conditions.

Our understanding of the plankton in LIS is greatly aided by comparisons with the pioneering work of Riley (1941, 1956) and others. Importantly, Lopez et al. (Chap. 6, in this volume) point out that nutrient and chlorophyll *a* levels have not changed in the open Sound over the past 60 years. The overall pattern is of a decreasing gradient from west to east in concentrations of N, chlorophyll *a*, and zooplankton. This trend, however, is dominated by comparisons between WLIS and ELIS, with concentrations variable in much of CLIS.

Pioneering research in LIS also has improved understanding of sediment biogeochemistry in deep-water estuarine habitat and the successional dynamics of benthic communities in response to disturbance (Rhoads et al. 1978; Rhoads and Germano 1982). Lopez et al. (Chap. 6, in this volume) provide an overview of the characteristics of the soft-sediment communities in LIS, noting general west to east gradients, with variations at smaller scales. Species richness is relatively low in the WLIS and CLIS basins, starts to increase in the eastern portion of the CLIS basin, and increases sharply east of the Connecticut River into ELIS (See Fig. 6.25 in Chap. 6, in this volume). Despite a number of Sound-wide surveys that provide a general understanding of the composition and structure of the seafloorcommunities of LIS (Pellegrino and Hubbard 1983; Reid et al. 1979; Schimmel et al. 1999), the temporal and spatial dynamics of benthic communities, both seasonally and inter-annually, and their response to environmental stressors (particularly in poorly characterized embayments) are not well understood. A more thorough understanding of the benthic communities in LIS will facilitate interpretation of temporal changes and assignment of causation to human and natural stressors, including climate change and ocean acidification.

Dredged sediment was historically disposed at many sites in LIS, commonly located just outside harbors adjacent to the dredged channel. Today disposal is confinedto four open water sites, which have been evaluated systematically, confirmingthat sediment disposal has immediate effects upon sessile epifauna and infauna. There do not appear to be long-term ecological effects, however, resulting from the disposal activities (Germano et al. 2011). Although dredged sediment disposal can modify habitat by altering grain-size composition and sediment-transport conditions by changing seabed elevation, there do not appear to be general changes in benthic processes or habitat at the disposal sites.

Foraminifera shells preserved in sediments have been used as proxies to reconstruct environmental changes over long time scales. *Ammonia* spp. and *Elphidium* spp. are the most common foraminifera genera in LIS, and higher ratios in *Ammonia* to *Elphidium* abundance have been interpreted as indicators of eutrophication (see Fig. 6.39 in Chap. 6, in this volume). Varekamp et al. (2010) have documented an increase in the ratio of *Ammonia* to *Elphidium* abundance, but they cite a number of possible causes including decreases in diatom productivity, an increase in an invasive cryptogenic species of *Ammonia*, or different hypoxic tolerances.

Of all the historic changes in the LIS ecosystem, perhaps those associated with declines in fisheryand wildlife resources resonate the most with the public. Both Weigold and Pillsbury (Chap. 1, in this volume) and Lopez et al. (Chap. 6, in the volume) recount the historic changes driven in large part by overharvesting, habitat loss, and pollution. Diadromous fishpopulations suffered firstfrom habitat loss and pollution, with current Atlantic salmon (*Salmo salar*) and American shad (*Alosa sapidissima*) runs a fraction of historic numbers along with declines in other herring species. Menhaden were harvested intensively all along the Atlantic coast. Oyster reefs in LIS were exploited with little thought of sustainability. The decline in these species has altered the energy flowin food webs, with likely cascading effects upon coastal ecosystem function (Nuttall et al. 2011).

The eastern oyster is of particular importance, providing multiple services as a habitat forming species in addition to its value as a fishery.Aggregates of shell topped by living oysters provide habitat for associated species, can lessen shoreline erosion by reducing wave energy, and biofilterthe water column (Peterson et al. 2003; Piazza et al. 2005; Dame et al. 1984). Beck et al. (2011) estimate oyster reefs have declined worldwide by 85 %, with a lesser loss in the United States. In a review of changes in oyster habitat in 24 estuaries across the United States, Zu Emergassen et al. (2012) estimate a loss of 64 %, with greater declines in biomass. Data on the current extent of oyster habitat in LIS were not available, preventing a comparison with historic estimates. While the extensive areas leased for oyster aquaculture in LIS increase the area and biomass of oysters beyond the limits of the historical natural beds, it is still likely that both the number and function of oysters in LIS are diminished compared to historic levels.

The geographic location and orientation of LIS is such that it hosts an interesting and unique assemblage of both cold- and warm-T tolerant species (Lopez et al., Chap. 6, in this volume). Some of the Arctic-cold-to-temperate-Atlantic assemblage includes species that originated in the Pacific and traveled to the Atlantic during paleo-migration. During the summer, many warm-temperate Atlantic species and some subtropical species appear, some of which may be endemic while others travel north via the Gulf Stream. Historic commercial and recreational catch records provide insight into the changes in populations over the centuries, and contemporary trends in finfish populations over more than the past two decades are aided by trawl surveys conducted by the Connecticut Department of Energy and Environmental Protection (CTDEEP) (Gottschall and Pacileo 2010). Since 1984, the overall biomass of finfishes in LIS has been relatively stable, but changes have occurred in individual types of fishes and likely in multi-species groups representing different guilds (Howell and Auster 2012). This is seen in the decrease in the overall abundance of fishes caught in the spring survey (driven by declines in epibenthic species such as winter flounder (*Pseudopleuronectes americanus*) and windowpane flounder (*Scophthalmus aquosus*), despite an increase in demersal species such as butterfish (*Peprilus triancanthus*) and scup (*Stenotomus chrysops*)) and an increase in the fall (particularly scup, butterfish, and weakfish (*Cynoscion regalis*)). Cold-adapted species have declined in abundance, particularly in spring; while warm-adapted have increased (see Fig. 6.49 in Chap. 6, in this volume). Section 7.6 of this chapter discusses the possible implications of climate on these trends.

Invasive species have also exerted a strong influence on the diversity and distribution of flora and fauna in LIS, dating back to the European exploration of the Americas. Some common species considered native are in fact introduced, including the common periwinkle (*Littorina littorea*) and a common red alga (*Neosiphonia harveyi*). Despite the descriptions of the modern biota of LIS by Weiss (1995) and Weiss et al. (1995), and by Schneider et al. (1979) for marine algae, defining the extent of past invasions is hampered by the lack of a scholarly atlas of the historical biota of LIS upon which to make comparisons. As a result, the number of non-native species in LIS, particularly for microscopic, cryptic, or invertebrate taxa, is speculative. Increased globalization, however, has accelerated species introductions, some of which become invasive, thus altering the ecology of LIS. Temperature increases enhance the survival of some introduced species and extend the range into LIS of other species.

7.5.2 Cross-Cutting Issues

Lopez et al. (Chap. 6, in this volume) review the interactions among physical, geochemical, and biological processes contributing to hypoxia in LIS. Clearly, inorganic nutrient loadings, primarily from wastewater discharges and land runoff, and photosynthetic production fuel the biological respiration that drives the system to hypoxia. Planktonic community respiration dominates benthic oxygen demand and respiration rates can deplete DO in days if not for physical ventilation. Despite a general understanding, work remains to more fully elucidate the mechanisms linking nutrient loading, physical forces, and the biology of the system.

The fate of primary production and linkages to hypoxia need to be better understood; there are uncertainties about the sinking and horizontal transport of primary production biomass, and imbalances between the sources and sinks of estimated carbon budgets in WLIS belie an incomplete understanding of ecosystem function. The Systemwide Eutrophication Model (SWEM) developed to support hypoxia management currently underestimates rates of both production and respiration, and improving its formulation is a priority for future model refinementand application. Remineralization of organic carbon and nitrificationof ammonium from sewage treatment plant discharges can contribute to hypoxia, but direct measurements using ^{15}N tracer and other methods are needed to assess their importance. Future modeling should also consider the consequences of changes in climate affecting the timing and fate of primary production upon oxygen dynamics.

In general, food web dynamics of LIS are relatively poorly known. Ecosystem modeling (e.g., Hakanson and Boulion 2003) would help relate trends in harvest and survey abundances to the biology of natural resources. The mechanisms involving important variables such as loss of keystone species, fishingpressure, T, and habitat alteration need to be better understood. Likewise, there is a need to better understand trophic linkages between primary production and apex predators. And perhaps surprisingly, considering much of the foundational work conducted in LIS, measurements of biomass and productivity of subtidal macrophytes and deep-water benthos for incorporation into food web models are sparse.

Expanded monitoring to assess critical habitats and biological communities is needed to develop a more holistic understanding of how the ecosystem will respond to continued nutrient reductions, invasive species, and climate change. Recent efforts by the LISS to increase monitoring of variables that provide sentinel insight to changes in biological communities, particularly from climate-driven changes, may be helpful in this regard. Continued and strengthened monitoring of key habitats and biological communities combined with carefully designed observations and experiments are needed to support models that will integrate our understanding of LIS.

7.6 Climate Changes Affecting LIS

Changes in the annual march of the water column seasons impact the biological processes of the Sound and hence potentially the entire ecosystem. Some organisms may adapt to these changes, but others may not. Growth and reproduction may be altered even if organisms can survive seasonal changes in T and S. Mobile organisms may alter their migration patterns and may be excluded from important food sources or spawning areas. Thus, simply altering the extremes of T and S or the duration of their seasonality can have significant impacts on many organisms.

Organisms living at the extremes of their geographical range may be particularly susceptible to stress from disease, hypoxia, or changes in physical conditions such as acidification.For example, seaweed populations may shift from the cool-temperate kelp (e.g., *Saccharina* spp.) and rockweed (*Fucus* spp.) species to more warm-temperate red algae (e.g., the red weed *Gracilaria tikvahiae*) or brown seaweed (e.g., *Sargassum* spp.). The impact of climate change, ocean acidification, and introduced species upon the Sound's native florais often anecdotal and points to the need for long-term monitoring in LIS.

As discussed by Lopez et al. (Chap. 6, in this volume), the American lobster population in LIS, living at the limit of its southern range, was decimated in 1999 (Pearce and Balcom 2005). Exceptionally high bottom water temperatures in the deep regions of the Sound seem to have played a significantrole in the mortality, perhaps even triggering it. In that year, the bottom water T abruptly increased about 2 °C at station D3 (off shore from Norwalk, CT) from August 4 to September 1 (Wilson and Swanson 2005). Much of this increase was associated with two water column destratifying events that mixed warm surface water to the bottom. The wind event of August 29, when a cold front passed over the area and the water column became isothermal, was the more important of the two. This type of environmental event could become more common as the ecosystem adjusts to a rapidly changing physical oceanographic setting.

Long Island Sound has been experiencing changes continuously in climate that affect its physical functioning as well as its ecosystem. If the rate of change increases rapidly, what were subtle changes in ecosystem reactions could now stress the ability of natural and human systems to adapt. For example, the Union of Concerned Scientists (2007) report that Northeast US air temperatures have been rising about 0.3 °C every ten years since 1970 and 0.7 °C in winter over the same period. They project that in the next several decades temperatures are likely to increase an additional 0.8 °C in summer and 1.9 °C in winter.

Perhaps one of the most important observations of the physical oceanography of LIS by O'Donnell et al. (Chap. 3, in this volume) is that the forces driving its physical functioning are quite variable; consequently the responses to these forces fluctuateconsiderably as well. Despite the variability, there are some generalities that can be made about the behavior of the Sound and what might occur in the context of climate change. For example, in recent research examining recurring hypoxia in LIS, Wilson et al. (2008) showed that in WLIS there was roughly a 1.5 °C change in the difference between summer-averaged surface and bottom water temperatures (ΔT) over the period 1946–2006 (Fig. 7.3). Most of that difference occurred because bottom waters are cooling. Over the same period, the summer-averaged bottom DO concentrations declined about 2 mg O_2/L, making hypoxic conditions more prevalent. Cooler bottom waters are a consequence of increased periods of water column stratification,partly in response to a long-term change in the directionality of regional winds. Over the period of investigation, the

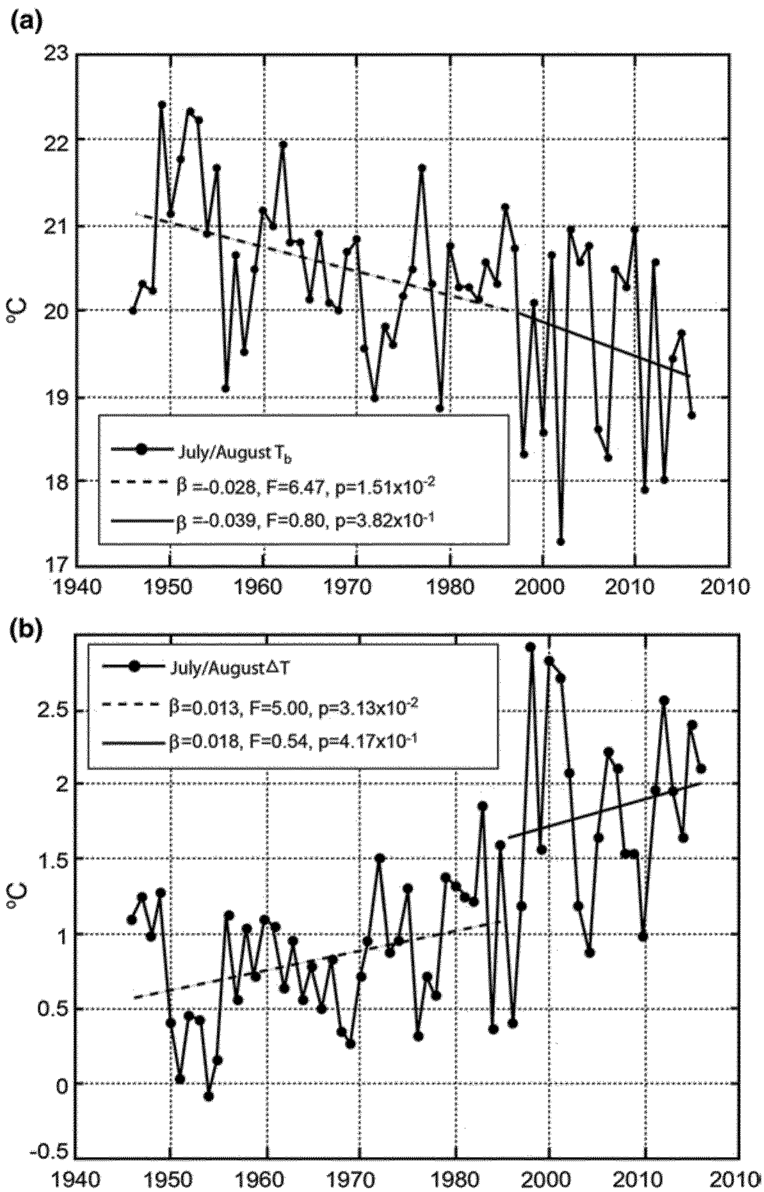

Fig. 7.3 *Top* Time series for bottom T at NYC DEP E10 averaged over July and August. *Bottom* Time series for surface-bottom T at NYC DEP E10 averaged over July and August

direction of the summertime wind fieldshifted about 30° from 245 °T (degrees True) to 215 °T—the latter being more conducive to maximizing water column stratification.It is not clear whether this change in wind direction is related to cli - mate change or the increasing heat island effect caused by continuing development throughout the area. The observed colder bottom water temperatures occur because stratificationis established earlier in the year and water column mixing is reduced. Thus, vernal warming of bottom waters does not take place as far into the spring as it did a few decades ago.

It is instructive to look at bottom water temperatures in the Sound—particularly during winter. As part of an analysis related to the 1999 lobster mortalities, the evolution of Sound-wide temperatures from 1991 to 2003 was examined for depths <20 m and those >20 m. The variability in winter minimum temperatures is noteworthy: the range over the 12 years was about 3 °C for depths <20 m and 4 °C for depths >20 m. The variability in summer maxima was somewhat less, being more on the order of 2–2.3 °C. As a result, changes in winter water column temperatures attributable to climate change may be as great as or greater than the often-discussed increases in summer maximum temperatures. Any significant long-term changes could not only alter the seasonal development of water column structure but also have a pronounced impact on survivability of organisms in the Sound.

Besides noting a change in the directionality of the winds, it is useful to examine wind speed. Robert Chant has plotted the north–south and east–west components of the daily average wind for the years 1947–1977 and 1977–2007 (Fig. 7.4). For both periods, the minimum in the average daily wind speed in the east–west direction (roughly aligning with the major axis of the Sound) occurs around day 130 in the calendar. But during the period 1977–2007, that minimum speed approached 0 m/s, about 1 m/s less than the minimum for the period 1947–1977. The minimum wind speed of 1 m/s for the period 1947–1977 is reached about 30 days earlier in the year for the period 1977–2007. Thus, the speed of the east–west component of the daily average wind speed is now reduced relative to the past and the historic minimum value is nearly a month earlier. The north–south component of mean daily wind speed is also about 0.5 m/s less between days 100–135 from 1977–2007 than it was over the period of 1947–1977. The vigor with which LIS surface waters are mixed to depth in spring is reduced, and this minimum wind value occurs earlier in the year than in the past.

Our local climate, as annually summarized for Central Park by *The New York Times*, has experienced about a 13 % increase in average annual precipitation over the last 20 years and perhaps as much as 20 % over 40 years. That increase is rather evenly distributed throughout the year. However, the big impact may be the form in which that precipitation is occurring (e.g., rain vs. snow). The Hudson River discharge has annually peaked in April or later about 79 % of the time over the 33 year period from 1946 through 1978. But for the last half of the record through 2010, this occurred only 61 % of the time; 39 % of the peak flowswere in March or earlier (US Geological Survey 2011).

The pattern for the Hudson River is consistent with broader regional patterns. Hodgkins et al. (2003) analyzed the 66 yearly records of stream flowin 27 unregulated rivers in New England. They found that for rivers dominated by snowmelt the timing of the winter-spring center of volume advanced 1–2 weeks earlier in the year. O'Donnell et al. (2010b) have found that winter-spring center of volume of the Connecticut River is also occurring earlier in the calendar year at a rate of 9 ± 2 days

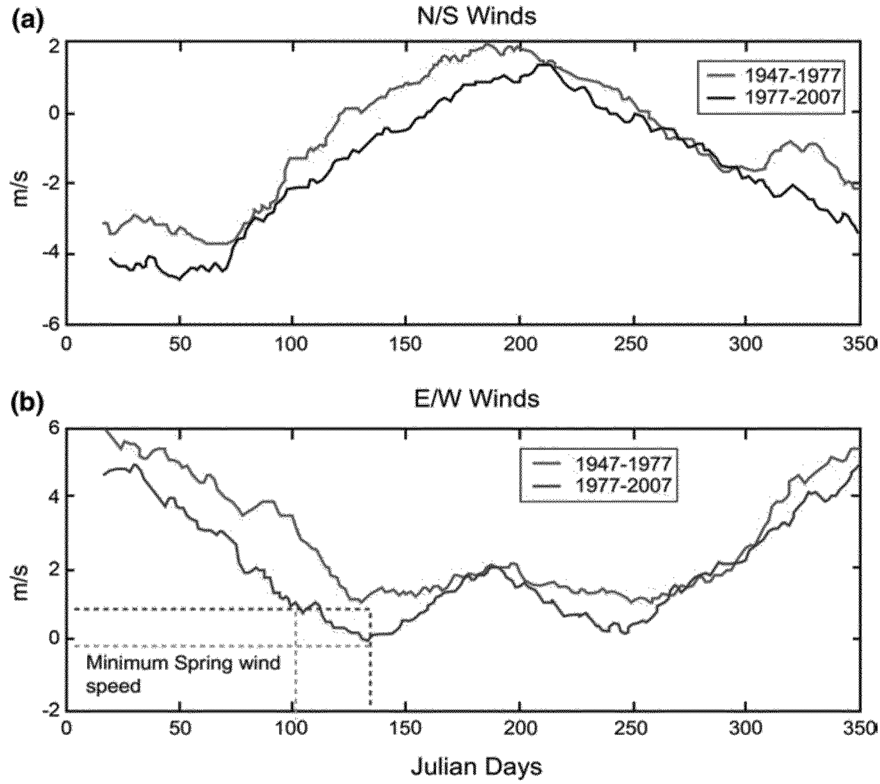

Fig. 7.4 The north–south and east–west components of wind speed (m/s over the calendar year (0–350 days) for the periods of 1947–1977 and 1977–2007 at LaGuardia Airport. *Source* Robert Chant, Institute of Marine and Coastal Sciences, Rutgers University

per 100 years, though the number of dams makes interpretations of causes more difficult.The Union of Concerned Scientists (2007), in a review of predicted climate changes in the State of New York,observes that snow is now wetter than in the past and opines that the snow season could be "cut roughly in half this century."

Water column stratificationin the Sound typically commences when the spring riverine freshet contributes fresh water to the system followed by vernal warming. Thus, haline stratificationmay be initiated earlier now compared to the past due to the earlier freshet. All signals point to climate change contributing measurably to earlier water column stratificationand therefore a longer period over which bottom waters are isolated from mixing with surface waters. The period of mixing of DO to depth from wind stress in LIS is reduced. As a consequence, there is now a longer period during the year that DO drawdown can take place and hypoxic conditions can be established. In the future, one might expect that the spring freshet will come still earlier or maybe disappear altogether if precipitation stored as snow declines. Either way, this will have a pronounced impact on water column structure in the Sound.

Changes in the timing of the spring freshet will also impact the delivery of allochthonous carbon and suspended sediment to LIS. For example, the organic carbon and sediment load of the Hudson River originates primarily from the nontidal portion of the Hudson (above the dam at Troy, NY) (Limburg et al. 1986). According to Wall et al. (2008), most of the suspended sediment load is transported through the lower Hudson from November through April—much of it in November and December and then again with the freshet in March and April. If the distribution of flowfrom rivers discharging to the Sound is altered as a consequence of climate change, one can expect that the discharge of organic/suspended sediment will likewise be modified. Water column transparency will change and conceivably primary production in the Sound as well.

It is revealing that the Hudson River, with its high anthropogenic N loading, is only "moderately susceptible" to eutrophication (Howarth et al. 2000) while the river flow is critical to that condition in LIS. Howarth et al. (2000) point out that the Hudson has a short residence time (days) for water and dissolved material, and that the water column is light-limited, thus inhibiting primary production. The Hudson River not only contributes to haline stratificationin WLIS, but also controls gravitational circulation through variations in the river's discharge. Hao and Wilson (2007) ascertained that the residence time of WLIS was on the order of months, and that period depended upon the degree of water column stratificationand the strength of gravitational circulation. Large freshwater discharge from the Hudson increases the latter, reducing residence time, but increasing haline stratification and decreasing mixing.

The Connecticut River is the largest source of fresh water to LIS and is important in freshening its mouth at the eastern end (O'Donnell et al., Chap. 3, in this volume). The thin plume of the river is greatly affected by the local tidal currents and during high river discharge an ebbing current can be observed some 20 km to the east, near The Race (O'Donnell et al., Chap. 3, in this volume). Apparently, not as much is known about the transport of carbon and suspended sediment in the Connecticut as compared with the Hudson. Knebel and Poppe (2000) contend that LIS has a "nearly 100 % …trapping efficiency" for fine-grained bottom sediments discharged by the Connecticut River, which are generally advected to the west, settling there. However, the gross transport processes of the Connecticut and how they might change in a warming climate are likely to be similar to those of the Hudson, since the climatic characteristics of their drainage basins are similar. Reductions in the spring freshet will likely cause the salt wedge to move upstream and change the characteristics and distribution of the brackish- and fresh-tidal marshes, which are designated as a wetland of international importance under the Ramsar Convention (an intergovernmental treaty established in Ramsar, Iran in 1971). The reduction in the spring freshet and earlier arrival will likely cause the loss of prolonged spring floodin the upstream fresh-tidal marshes, reducing or eliminating their value as important stopover sites for spring migrating waterfowl.

Climate change also could affect delivery of fresh water to the Sound through changes between precipitation (P) and evaporation (E). Koppelman et al. (1976), using data from 1953–1954, estimated that P minus E for LIS to be about 31 cm where P:E is 1:0.75. Krug et al. (1990) show that the annual precipitation rate in Connecticut is roughly twice that of evapotranspiration. Long Island is much the same (Central Pine Barrens Joint Planning and Policy Commission 1995). However, Kowalsick (2012) estimated monthly evapotranspiration rates from 2006 to 2009 during the growing season for Long Island and found spring and fall rates were one-third of summer rates. Since precipitation rates are fairly uniform throughout the year, the difference between precipitation and evapotranspiration is quite variable. Changes in either with climate change could significantlyalter the delivery of fresh water to the Sound.

The Union of Concerned Scientists (2007) postulates that our region will experience stronger and more frequent precipitation events because of global warming. This will undoubtedly translate into an increase in temporary shellfishbed and beach closures. Depending on the frequency of such events, permanent closures might also increase. Changes in cloud cover could have a pronounced effect on eutrophication and ecological functioning in LIS by altering primary productivity and thus influencingeutrophication. In Narragansett Bay, Nixon et al. (2009) associate decreases in annual and summer mean phytoplankton abundance with warming of the water, especially during winter, and to increased cloudiness. The subsequent decline in organic matter deposition to the bay has reduced benthic metabolism.

Sallenger et al. (2012) identifiedthe northeast coast of the United States as experiencing accelerated sea level rise relative to the global mean. The average rate of relative sea level rise as determined from four NOAA tide gauges (New London, Bridgeport, Kings Point/Willets Point, Montauk) around the Sound over the period of 1986–2010 is 4.6 ± 1.4 mm/y (Fig. 7.5). This rate, determined using three-year running averages of annual sea level values at the respective stations, is significant($p = 0.01$). Thus, over the period of the LISS, relative sea level has risen about 11.5 cm. Climate prediction models suggest that this rate may increase substantially. There is concern that low-lying areas will be floodedand that wetlands will be lost. It is also likely that erosional processes along the Long Island shore will be altered as a consequence of this projected sea level rise.

While it is evident from O'Donnell et al. (Chap. 3, in this volume) that LIS's wave fieldwill not be altered due to sea level rise, its directionality could change as the wind fieldshifts. Some areas may be more exposed to the influenceof waves, others less. The Long Island shoreline is perhaps the most vulnerable as the steep slopes of sand, gravel, and glacial till slump due to undercutting of the toe of these steep bluffs by wind waves generated at the higher sea level. Shepard and Wanless (1971) reported that in the eighteenth and nineteenth centuries prominent headlands were eroded some 150 m in the vicinity of Oak Neck on Long Island. Davies et al. (1973) found a bluff recession rate in the 20th century of some 0.5 m/y with a range of 0–1.6 m/y at 19 locations from Oak Neck Point near Oyster Bay to Orient Point, a distance of some 97 km. This bluff erosion feeds the littoral drift and the beaches of the north shore (Bokuniewicz and Tanski 1983). For example, the bluffs of Nissequogue currently feed Long Beach, causing the spit to prograde to the east-northeast about 1.8 m/y (Swanson and Bowman, in preparation). Bokuniewicz and Tanski (1983), in their sediment budget resulting from bluff erosion, estimate that about 85 % of the eroded

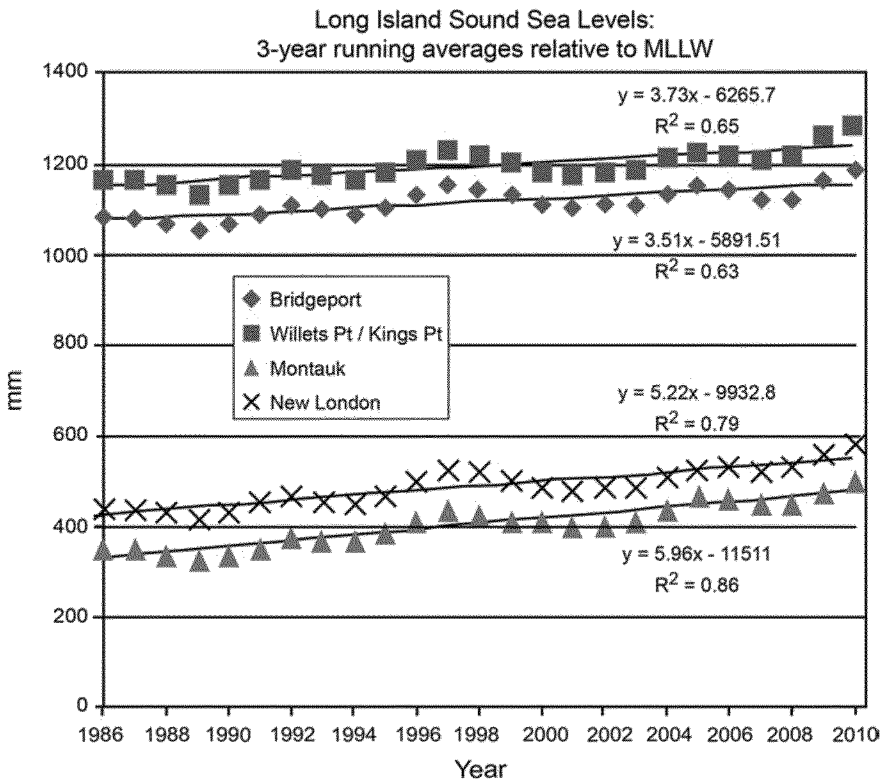

Fig. 7.5 Three-year running averages of mean sea level relative to mean low low water (MLLW) at Bridgeport, Willets Point/Kings Point, Montauk and New London and their respective relative sea level rise rates, 1986–2010

material ends up in the deep waters of the Sound with about 3 % going to wetlands; very little permanently remains on the beaches, hence they are generally receding.

There are additional, less obvious, possible impacts of alterations to the physics of the Sound associated with climate change. For example, sea level rise will cause the water table to rise in coastal areas as a consequence of saltwater intrusion, causing low-lying areas along the shoreline to experience a greater likelihood of floodingthan that due to sea level alone. Or as sea level rises, the tombolo that forms Truman Beach on the north fork of Long Island will become a mere shoal, making the physics of the mouth of the Sound even more complex than at present.

The changes in climate that influencethe physical oceanography of LIS will reverberate throughout the ecosystem. As a result, the magnitude and time frames over which physical processes operate need to be better understood and accounted for to support management. This is particularly true in the design aspects of coastal development and related infrastructure initiatives. It is also true for diagnosing and responding to LIS's lobster mortality events and the chronic annual hypoxia, since both appear to be closely tied to altered physical drivers that may further change in the coming decades.

7.7 Integrating Science and Management

7.7.1 Management Jurisdiction

Although functionally an estuary, according to a 1985 US Supreme Court decision, LIS is a juridical bay. The court judged Long Island an extension of the mainland, considering physical connections (bridges, tunnels, etc.) and historical and political ties rather than strict oceanographic or geological interpretations of whether or not it is an island (Swanson 1989). The closing line (demarcates inland waters from the 3-nautical mile marginal seas of the states) at the mouth of the Sound, as determined by the court, runs from Montauk Point, NY to Watch Hill Point, RI. This ruling is important because it established the Sound as "internal waters" in a legal and navigational sense, which means that it falls, for the most part, under the authority of the applicable coastal states (Westerman 1987)—Connecticut, New York, and to a limited degree Rhode Island. Thus, the states have primary responsibility for many aspects pertaining to the management of the Sound and will need to take leaderships roles in implementing such initiatives as ecosystem-based management (EBM) and coastal and marine spatial planning (CMSP).

7.7.2 Ecosystem-Based Management

7.7.2.1 Ecosystem-Based Management Concepts

President Obama's Executive Order 13547 (2010) adopted the recommendations of the Interagency Ocean Policy Task Force (Council on Environmental Quality 2010), making ecosystem-based management (EBM) a foundational principle of federal management of US coastal waters and resources. The executive order was preceded nationally by the recommendations of the Pew Oceans Commission (2003) and the US Commission on Ocean Policy (2004), and in New York State by the passage of the New York Ocean and Great Lakes Ecosystem Conservation Act (2006), which adopted EBM policies for the management of New York's marine and Great Lakes ecosystems and established a conservation council to implement them. Although the specific approaches for EBM programs vary, the general tenets for marine systems can be summarized as follows (McLeod et al. 2005):

- Plan on an ecosystem level, considering cumulative impacts and long-term changes.
- Involve multiple stakeholders and integrate the full spectrum of ecosystem services supporting human wants and needs.
- Develop cross-jurisdictional goals through formal agreements among multiple levels of government and the private sector.

- Implement programs through coordinated strategies that recognize shared responsibility across levels of government and the private sector, but delineate clear responsibilities for accountability.
- Incorporate adaptive management that acknowledges uncertainty in our understanding, fosters testing of alternate management approaches, and allows for adjustments based on improved information.
- Establish long-term observation, modeling, and research programs that support adaptive management by improving ecosystem understanding and evaluating the effectiveness of management action.

These concepts provide a framework for both analysis and management that accounts for the complex interrelationships of human society, economics, and the environment. Societal needs and the economic consequences of activities to ecosystem services that society relies upon are vital elements to be integrated into management. Otherwise, EBM is just another form of environmental management, to be treated as a lower priority that can be addressed after tackling more pressing social and economic needs, instead of an integral part of meeting those needs.

How can these principles be best put into practice at the estuary scale? How can science be integrated across disciplines to interpret and forecast changes in coastal systems? What obstacles exist in facilitating cross-jurisdictional planning and permitting (e.g., for energy production or transmission proposals)? How do existing statutory and policy requirements within those jurisdictions support or conflictwith these principles? For example, do policies for the development and implementation of pollution total maximum daily loads (TMDLs) under the CWA provide mechanisms for adaptive management? How can estuary-specificrestoration efforts complement and benefit from regional fishery management?

We review these questions from the perspective of LIS. For context, we present essential elements of the CWA, providing specificexamples of current program policies in synchrony or in conflictwith the principles of EBM, along with recommendations for integration within the constraints of current technology limitations, statutes, regulations, and policies. We then recommend a general framework and specificactions to support ongoing management. Our intent is to demonstrate the utility of this analysis for LIS and help inform the debate on how to strengthen coastal ecosystem protection nationally.

7.7.2.2 The Context for Ecosystem-Based Management on the Estuary Scale

Estuarine and coastal systems have been impaired primarily from overharvesting, habitat loss and degradation, and pollution (Lotze et al. 2006). Invasive species and arguably climate change have had a lesser impact to date but may become more influentialin the future (Lotze et al. 2006). To address these stressors successfully, EBM must foster integrated and coordinated responses among fisheries, coastal zone, and water quality management programs (Rosenberg and McLeod

2005). Each of these programs, however, operates at different scales, none specifically at the level of the LIS ecosystem. For example, fisheries management will be regional, reflecting the migratory nature of many fish stocks. Coastal zone management for LIS is implemented on a state scale by Connecticut and New York under authority of the Coastal Zone Management Act through NOAA. Water quality management is both state and regional, reflecting a LIS watershed that extends beyond the coastal states of Connecticut, New York, and Rhode Island through portions of Massachusetts, New Hampshire, and Vermont. Each of these programs is conducted under separate federal authorizing statutes and administered by different agencies, primarily NOAA for fisheries and coastal management, and USEPA for water quality. Other federal agencies have significant roles: the US Department of Agriculture for nonpoint source runoff, the USGS for water resource research and monitoring, and the US Fish and Wildlife Service for habitat and species management are just three examples. These federal programs often are delegated or administered jointly with state agencies.

Although created prior to the common use of EBM as a term of reference, the National Estuary Program (NEP) was established in 1987 under Section 320 of the CWA to support comprehensive and inclusive planning with an ecosystem focus. Additional legislation specific to LIS that passed in 1990 further strengthened USEPA's role in coordinating implementation strategies through cross-jurisdictional partnerships. Reflecting its origin within the CWA, however, the NEP legislation directs development of a CCMP that "…recommends priority corrective actions and compliance schedules addressing point and nonpoint sources of pollution to restore and maintain the chemical, physical, and biological integrity of the estuary…," a narrower construct than current EBM approaches would take in considering threats to ecosystem services. In practice, most estuary programs have targeted additional stressors of ecosystem function, including degradation and loss of habitat, and invasive species.

Despite the integrating intentions of the above-mentioned legislation, even a comprehensive program cannot be all-inclusive; consideration of the ecosystem's scale and impairments in relation to the scale and function of existing management programs is needed to set priorities and effectively direct management responses. For example, the LISS, one of 28 NEPs, decided early not to involve itself organizationally with fishery management, recognizing that there are existing multijurisdictional planning programs (the New England and Mid-Atlantic fishery management councils, established under the Magnuson-Stevens Fishery Conservation and Management Act of 1976, and the Atlantic States Marine Fishery Commission, established in 1942) that operate at the appropriate regional scale. Instead, the LISS has focused on water and habitat quality within LIS, which can affect species abundance and diversity. While avoiding duplication of effort, this approach has led to criticism by some that the LISS has not been engaged directly in the restoration of one of the most public of estuarine ecosystem services—abundant and diverse populations of commercially- and recreationally-important species. The lesson is that estuary management programs do not need to tackle all aspects of the ecosystem. An assessment of gaps or limitations to effective EBM of the specific ecosystem services in question is needed before designing an effective program.

Another example of priority-setting for LIS is in the area of water pollution. Although contamination from pathogens and toxic substances initially was considered to cause the major impairments to human use and ecosystem health of LIS, water quality surveys supported by LISS in 1986 and 1987 documented hypoxia as more severe and covering a larger area than previously measured (Welsh and Eller 1991). The need to address nutrient levels on an ecosystem level, considering assimilative capacity, vaulted hypoxia management as a priority over pathogen and toxic substance effects, both of which had already been markedly reduced through national management programs (e.g., technology-based limits for industry, combined sewer overflowremediation, product bans, and wastewater pretreatment requirements). For example, air and water releases of industrial chemicals from sources in the Connecticut and New York portions of the LIS watershed declined by more than 90 % between 1988 and 2008 (LISS 2010). Releases watershed-wide declined by 74 % from 2001 to 2010 (USEPA 2010). Product bans for PCBs in 1979 and for lead in gasoline as part of the 1990 Clean Air Act amendments have led to reductions of these chemicals in the sediments and biota of LIS (Varekamp et al., Chap. 5, in this volume). Controls of phosphorus (P) in response to localized instances of eutrophication of freshwater resources had been in place for decades, but watershed sources of N to the Sound remained without assessment or control. Here, too, an assessment of current environmental conditions and gaps in existing management programs was essential to setting priorities for LIS.

7.7.2.3 Total Maximum Daily Loads and Ecosystem-Based Management

At the heart of EBM is the recognition of human society as an integral component of ecosystems and their functioning. The goal of management is to maximize the services to human society that the ecosystem supports, recognizing that there are conflictsand tradeoffs in the provision of those services. But for managing water quality, federal water quality standards regulation established under the CWA requires states to specify the appropriate water uses to be achieved and protected for recreation and the protection and propagation of wildlife. States then adopt criteria to protect these designated water uses as part of the state water quality standards package. The concepts of ecosystem services as definedunder EBM and of designated uses as applied under the CWA bear some resemblance, but they are not interchangeable, and for water quality management of LIS, the latter has primacy. States can designate new uses, or create subcategories of existing uses, that require less-stringent criteria, but only through a formal assessment called a use attainability analysis. A detailed review of water quality regulations under the CWA is beyond the scope of this discussion; however, the key point is that these regulations are not antiquated notions of how to manage water quality. These statutes and resulting regulations are the legal, enforceable framework in the United States. For water quality management, the concepts of EBM must be adapted to the CWA (either as it currently stands or as modified through legislation).

The application of adaptive management, another key tenet of EBM, to water quality protection also is instructive. By explicitly acknowledging uncertainty in our understanding of both the natural and social sciences relating to estuarine management, adaptive management ideally fosters integration of science into management through the testing, measurement, and assessment of alternate management approaches. Adaptive management is not organic to many of the implementing statutes under which water quality management is conducted. Perhaps most relevant to LIS are the policies regarding numeric criteria and the development and implementation of TMDLs for pollutants that impair water quality. These policies and regulatory guidelines can constrain the flexibilitynecessary for effective adaptive management (National Research Council 2011). Before undertaking the effort needed for successful application of adaptive management, consideration of its benefitsis warranted. Adaptive management within a TMDL framework may not be justifiedwhen the degree of uncertainty is low or when the costs of errors resulting from that uncertainty are acceptable (Shabman et al. 2007).

Total maximum daily loads require precision in identifying allocations to attain water quality standards, but the science upon which such calculations are based, let alone how comprehensively the science is applied, is often filledwith uncertainty. The TMDL program considers uncertainty in specificallyallocating loading to a Margin of Safety (MOS), which is meant to set allocations conservatively to attain water quality standards. As a result, the TMDL framework is at odds immediately with EBM's emphasis on acknowledging uncertainty, as well as adaptive management protocols that address that uncertainty. The MOS concept was developed primarily with toxic contaminants in mind to account for the uncertainty of synergistic effects and bioaccumulation or biomagnificationin living organisms. It can be argued that the MOS for nutrients extends both above and below a target concentration or load based upon weight-of-evidence determinations set to attain a trophic condition, or secondary indicator (e.g., DO), that has a range of outcomes to nutrient control that can be quite broad. "The lower the better" paradigm for xenobiotics does not necessarily apply to nutrients. For example, excessive nutrient control could change nutrient balances, and thus the limiting nutrient in LIS, which could have major consequences for ecosystem structure and function.

To reconcile precision and uncertainty, USEPA TMDL guidance wisely allows for "phased TMDLs" in situations wherein limited existing data are used to develop a TMDL and wherein the use of additional data would likely increase the accuracy of the TMDL load calculation. In such cases the TMDL, in addition to allocating and implementing controls to attain water quality standards, can include schedules for additional data collection and analysis to refinethe TMDL in a phased approach. A phased TMDL may include activities to test and evaluate alternate management approaches, but it still must set allocations among pollution sources, with a reasonable assurance of being implemented and with a MOS, necessary to achieve water quality standards. Hence, there remains some tension between the requirement for specificityin setting firmallocations among sources in TMDLs, a departure from which would require USEPA approval, and an adaptive implementation approach that might over time identify alternate approaches to meeting water quality standards, or bring new information to bear on their attainability. There remains a need for clearer guidance on provisions for flexibleallocations, particularly adjustments between wasteload (permitted point sources) and load allocations (unpermitted nonpoint sources). Ideally, the uncertainty in predicted outcomes would be acknowledged in TMDLs and in the scope and pace of investments (e.g., advanced sewage treatment) to achieve those outcomes.

Increased data collection and analysis (including research into ecosystem structure and function) would likely improve the accuracy of calculations of most TMDLs, but they are particularly relevant to the management of eutrophication in coastal waters. As the science of coastal eutrophication still is evolving (Cloern 2001), with the relationship between nutrient loading and adverse impacts in estuaries being complex and often nonlinear (Kemp et al. 2009), often it is difficultto predict how the water body will react to load reductions. Regime shifts—changes in food webs and nutrient processing—can alter the assimilative capacity of estuaries to nutrient loading, and the trajectory and rate of response to controls (Duarte et al. 2009). The drastic decline in bivalve populations or beds of submerged aquatic vegetation in many coastal systems, resulting in a loss of ecosystem services related to nutrient uptake, processing, and denitrification,may in effect move the goal posts for restoration efforts (Newell 2004; Kemp et al. 2005; Testa and Kemp 2012).

Predicting the response of coastal systems to local forcing (e.g., nutrient reductions) is complicated further by larger-scale influences driven by climate change. Fulweiler et al. (2010) observed declines in sediment oxygen demand and dissolved inorganic N fluxesin the upper portion of Narragansett Bay related to decreases in primary production and shifts in bloom phenology caused not by local nutrient management but by climate change. Management decisions that do not account for these influenceswill likely not universally achieve the predicted outcomes. In LIS, managing outcomes will need to take into account the changes in physical forcing that are lengthening the stratification season and increasing susceptibility to hypoxia.

7.7.2.4 The Long Island Sound Total Maximum Daily Load and Ecosystem-Based Management

Hypoxia (low dissolved oxygen), fueled by nutrient enrichment, is considered Long Island Sound's most pressing environmental problem (LISS 1994, Lopez et al., Chap. 6, in this volume). Both Connecticut and New York have DO water quality standards and numeric criteria applicable to LIS. Historical and current water quality monitoring and modeling show that during portions of the summer months substantial areas of the deep waters of WLIS do not meet states' DO criteria. Because of these identifiedCWA "impairments," the two states were in a position of having to develop a TMDL for DO. With research and monitoring fostered by the LISS since the mid-1980s, planning focused on N as the most important nutrient to mitigate the development of excess phytoplankton blooms and consequent hypoxia (Howarth and Marino 2006), an approach supported by subsequent monitoring and modeling of LIS. As there are no adopted numeric nutrient criteria in Connecticut or New York applicable to LIS, the LISS supported the states' efforts to translate numeric DO criteria endpoints into allowable N loads within a TMDL.

In 2000, after more than a decade of effort, Connecticut and New York submitted to the USEPA a TMDL (CTDEP and NYSDEC 2000) that set allocations for N to improve DO conditions. The allocations for N were set at a 58.5 % reduction from an estimated 1990 baseline of controllable point and nonpoint sources originating in Connecticut and New York (10 % from urban and agricultural runoff and the balance from point sources, primarily WWTFs). The TMDL also set planning targets for N control in the tributary states of Massachusetts, New Hampshire, and Vermont (a 25 % reduction from point sources and a 10 % reduction in nonpoint sources), and considered reductions in atmospheric deposition of N from air emission control programs (an 18 % reduction based upon model forecasts of national and regional Clean Air Act initiatives). Despite this unprecedented proposal for N control, small portions of the Sound would still not meet state water quality standards, a requirement of a TMDL. To fill the gap, the TMDL proposed assessment of alternative technologies including mechanical aeration of the residual, non-complying areas or bioextraction of nutrients by aquaculture of shellfish and seaweed.

At the time of its approval, and for a decade after until the completion of the Chesapeake Bay nutrient TMDL in 2010, the LIS TMDL was the most complex and comprehensive in the nation, setting N allocations for more than 100 WWTFs in two states and making recommendations for allocations in three other watershed states. Its development spurred policy innovations in three areas of management: equivalency factors for pollutant trading, compliance schedules within pollutant discharge permits beyond their 5-year term, and incorporation of alternative technologies (e.g., bioextraction of nutrients by shellfish and seaweed aquaculture).

The LIS TMDL established a flexible framework for the states to modify wasteload allocations among wastewater treatment plants without USEPA approval through pollutant trading approaches. By including equivalency factors in the TMDL that accounted for the relative impact of different sources on water quality based on geographic location, states could reallocate N source reductions among individual sources as long as the same or better predicted water quality improvement would result. This allowed flexibility to dischargers in meeting permit limits and allowed them to plan for N removal at the time when economics were most favorable to their facility, without a negotiated permit compliance schedule. This flexibility does not extend to reallocations between load and wasteload allocations, which require USEPA approval in a revised TMDL.

The 2000 LIS TMDL was constructed as a phased TMDL to allow for ongoing work to address uncertainty and support adjustments over time. Marine DO criteria (USEPA 2000) that had been concurrently under development would provide a firmer scientific basis for state water quality standards. Additional modeling was in the works, and plans for more inclusive management throughout the basin were proposed and discussed with a Connecticut River Nitrogen Work Group, coordinated by the New England Water Pollution Control Commission (NEIWPCC).

Although a TMDL is not a strict enforcement tool, underlying enforceable mechanisms mandate that CWA National Pollutant Discharge Elimination System (NPDES) permit limits meet the requirements of the TMDL for pollutant-load reductions. For non-regulated sources, primarily nonpoint sources, "reasonable assurances" must be provided by the states that identify how the load allocation will be met. The TMDL also should include an implementation schedule, although USEPA approval of a TMDL does not include a review and approval of implementation plans.

Connecticut and New York have chosen different approaches and uses of regulatory authorities to meet the wasteload allocation from WWTFs in their respective states. Both include innovations in permitting that take advantage of economics to minimize costs to municipalities and their rate payers. The New York State Department of Environmental Conservation (NYSDEC) has issued traditional NPDES permits that limit N loads for individual New York WWTFs, but has used or allowed a "bubble" approach by grouped, regulated administrative entity—New York City, Westchester County, Nassau County, and Suffolk County. This has provided a distinct advantage for N control for New York City in particular, where WWTFs, including related CSO loads, provide a high percentage of the N load to the "edge of Sound" along the East River. Because a portion of the load is swept into New York Harbor by prevailing tidal currents in the East River (Blumberg and Pritchard 1997), four of the six facilities along the East River, i.e., those most proximate to WLIS, were targeted for more aggressive management, providing relief for the two facilities closer to New York Harbor. Due to the cost and complexity of the upgrades, NYSDEC has established separate consent agreements with both New York City and Westchester County that extend the time for full compliance to 2017.

Connecticut chose a different alternative to managing 79 municipal facilities distributed throughout the state by implementing a relatively new concept, pollutant "trading," using a watershed-based N general permit and an oversight Nitrogen Credit Advisory Board to run a Nitrogen Credit Exchange (NCE). Although not a true free-market enterprise, the NCE provides an incentive for those facilities with low marginal costs for N removal to sell credits to those facilities with higher marginal treatment costs. The NCE has, as of 2012, been in operation for 10 years, and currently is on schedule to meet the 2014 target for N control from those facilities.

Through implementation of the TMDL, nutrient inputs to LIS for all major input categories (WWTFs, atmospheric deposition, tributaries) have decreased significantlyin several watersheds (See Sect. 7.4.4 and Varekamp et.al., Chap. 5, in this volume). This is the result of reductions from WWTF inputs as well as regional reductions in atmospheric emissions. Water quality programs to address polluted runoff also are evolving, with green infrastructure and low impact development the most notable examples. The downward trend in N loading is occurring even as the human population in the watershed has increased by about 3.5 % from 2000–2010 and development in Connecticut and New York portions of the watershed has increased by about 15 % in the 1985–2010 period. However, some caution is warranted. Tributary concentrations of N generally show no significant trend in recent years, with evidence of an uptick in delivered loads with higher flow.Trends in concentrations or fluxesof N in groundwater also are much less definitive,but there is clear evidence of increase groundwater concentrations of N in Suffolk County, NY. Delivery of groundwater to LIS is subject to time lags attributable to transport, which will delay the response to changes in management or land use (Mullaney, 2007).

As discussed in earlier chapters, the science of the mechanisms of eutrophication and hypoxia in the Sound has advanced in the past decade. High-frequency, time-series measurements, in particular, have helped elucidate the physical factors that influence the seasonal and annual variability in hypoxia. Core data present a reconstruction of hypoxic conditions dating back centuries. Current evaluations of the TMDL incorporate a number of technical enhancements (updated computer modeling, refined load estimates, etc.) as well as revised water quality standards for DO. Any future revisions of the TMDL, however, still will need to deal with considerable uncertainty and would benefit from phasing and adaptive management. To be successful, adaptive management must be embraced fully, particularly to incorporate management of waterbody processing of nutrients, wherein much of the uncertainty lies, in addition to watershed loading. Adaptive management also requires incorporation of flexible allocation schemes that retain specificity and accountability. And, perhaps most significantly, adaptive management must incorporate schedules reflective of the extensive time lag between implementation of a practice and the realization of the environmental benefit. For example, reduced nutrient delivery to receiving water through groundwater sources can be delayed years after effective control practices are put into place (Bachman et al. 1998; Focazio et al. 1998).

Modeling and monitoring supported the view that P can limit primary production in some areas of the Sound during portions of the year; nevertheless, the 2000 TMDL focused on N as the primary limiting nutrient. With the national initiative to develop numeric nutrient criteria for P to protect freshwater systems from eutrophication, however, it is likely that future P loading from the watershed also will decline from current levels. States increasingly are required to incorporate P permit limits for discharges to wastewater-dominated fresh waters. For example, in 2011, Connecticut came to agreement with the USEPA to incorporate P limits on all municipal discharges to non-tidal fresh waters upon permit renewal, which will lower the total load of P from that source substantially (http://www.ct.gov/dep/cwp/view.asp?a=2719&q=474130&depNav_GID=1654). Decreases in P loading from the LIS watershed from implementation of freshwater P criteria should be considered in evaluating water quality responses. Likewise, watershed reductions in N to achieve downstream targets for LIS should be evaluated for benefits to inland waters, since there is evidence of benefits to dual nutrient controls (Lewis et al. 2011).

Despite overall progress in reducing the inputs of nutrients to the Sound, analysis to date has not shown a significant improvement in hypoxia. This is attributable to a number of factors that are articulated within this volume, including pressures on the Sound related to large-scale climatic shifts (wind direction and magnitude, increased water temperatures and associated stratification). The response in hypoxic condition to regional management efforts focused on N may not be immediate, and intermediate components such as nutrient levels, phytoplankton production, water clarity, and eelgrass must continue to be monitored and evaluated, with management likely adapted. For example, in 1987, Mumford Cove, an embayment in eastern Connecticut, contained a near monoculture of Sea lettuce (*Ulva lactuca)*, a green macroalgae, with no seagrass found throughout the cove (Curtis and Dunbar 1985). By 1988, less than one year after the diversion of a wastewater treatment plant discharge from the cove to the Thames River, the biomass of sea lettuce was reduced by 99 % (French et al. 1989). Within 10 years after diversion, eelgrass was once again the dominant primary producer in the cove (see case study at http://www.lisrc.uconn.edu/eelgrass/Mumford.html).

Watershed loading targets allocated among sources, with schedules for implementation, are needed in combination with policies and programs to enhance populations of shellfishand other filterfeeders, restore submerged aquatic vegetation, and restore wetlands. Tradeoffs among components of the ecosystem and the services provided will need to be acknowledged. For example, reducing phytoplankton production through nutrient loading controls may increase the distribution of submerged aquatic vegetation while simultaneously reducing growth of some species of bivalves (Wall et al. 2011). Similarly, the indirect benefitsof environmental quality management aimed at LIS support the local economy and lifestyle throughout the watershed. Concepts of healthy watersheds can address a multitude of ecosystem services and garner more local support if the community benefitsare realized, as well as the downstream benefits that are shared regionally (USEPA 2012). Flexibility should continue to be given to a phased TMDL for LIS that addresses uncertainty and crafts an adaptive systems approach that integrates watershed load reduction programs with enhanced nutrient processing to attain water quality standards, restore designated uses, and more broadly restore ecosystem services basin-wide.

7.7.2.5 ManagementApplication

Boesch et al. (2000) assessed the application of scientificknowledge about estuar - ies to site-specificmanagement, reviewing case studies, and highlighting the factors supporting or impeding success. Among successful traits are the availability of long-term scientificdata to document problems and an institutional structure that includes a multiple range of stakeholders—agencies, scientists, user groups, conservation organizations, and the public—to develop response strategies. With the maturation over the past quarter century of collaborative programs managing coastal and estuarine waters, both nationally (e.g., Chesapeake Bay, Gulf of Mexico, South Florida, 28 National Estuary Programs) and internationally, best practices have emerged for science, collaboration, communication, and implementation. One such practice is to synthesize the underlying science as a foundation for management (see Abal et al. 2005, Dennison et al. 2009; Desbonnet and Costa-Pierce 2008; Levinton and Waldman 2006).

While the science of LIS has advanced greatly over the past quarter century, better informing planning and management efforts, there remain gaps that hinder effective management. These science gaps and the priority needs, identifiedin prior chapters, are summarized in Figs. 7.6 and 7.7. While the gaps and research needs are drawn from the estuarine, freshwater, and terrestrial scientificcommunities, this book reflectsa bias toward the estuary. Further dialogue and collaboration among these communities, as well as social scientists, will be needed to integrate watershed-waterbody scale processes. No attempt is made to prioritize among these needs, which will vary depending on the mission and resources of individual programs.

The synthesis of LIS attempted here is particularly timely, with planning underway to update and revise both the LIS CCMP (LISS 1994) and the N TMDL (CTDEP and NYSDEC 2000). Combined with a community vision for LIS developed in 2011 by the LISS Citizens Advisory Committee, it fulfillskey elements of enhancing application of EBM to LIS.

Boesch et al. (2006) emphasize that true synthesis requires that the science be integrated and applied to questions facing management, supporting formulation of response strategies. Based on our interpretation of both the underlying state of the science of LIS, the general tenets for EBM, and our interpretation of the public's vision and hopes for the waterbody, we offer ten recommendations for enhancing management of LIS (Fig. 7.8).

Geology
- Reduce ambiguity regarding the thickness of in-place Coastal Plain vs. glacial deposits along the north shore of Long Island leads, which to a potential misunderstanding of groundwater flow and discharges to LIS.
- Better understand the nature and timing of marine transgressions to the Sound.
- Better understand potential seismicity in LIS.

Physical Oceanography
- Better characterize lateral structure with particular emphasis on the smaller bays and inlets. Characterizing the exchange between LIS and its bays, harbors, and inlets will require higher resolution measurements.
- Undertake additional seafloor observations to better understand sediment-water interactions.
- Reduce uncertainty in understanding local effects of global climate change by increasing measurements to better describe changes in all habitats.
- Undertake high resolution bathymetry and topography measurement to support predictions of coastal hazards and flooding from storms/sea level rise coupled with higher density sea level measurements.

Geochemistry
- Better characterize the role of sediment processes in the sources, transport, and fate of nutrients and other compounds.
- Clarify the relationship between embayments and LIS proper, including linkages between phytoplankton production in the main stem and organic matter accumulation in embayment sediments.

Pollution
- Better understand the dynamics of pH and dissolved inorganic carbon.
- Evaluate risk from emerging contaminants.
- Characterize the sediment load and sources as part of a dredged material management program.

Fig. 7.6 Gaps and key research needs to support management

Ecology/Biology

3 nĉrease quantitative data on spatial and temporal features in the littoral zone to quantify what has been lost and better evaluate how to restore.

3Tidal Marshes:

a Better understand the potential link between pathogens and other possible causes of sudden vegetation dieback and to evaluate its effect on important marsh fauna and flora.
b Determine the importance of tidal pools to important marsh fauna.
c Better evaluate the contributions of restored tidal marshes to marsh birds, plants, and animal communities.
d Evaluate the ecological implications of the spread of *Phragmites australis*, an important non-
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3 Better evaluate the response of seagrass to stress.

3 Fate of primary production and linkages to hypoxia need to be better understood. There are uncertainties to sinking and horizontal export of primary production and imbalances between
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3 Deep water benthos:

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(particularly for coarse grain sediment successional dynamics, response to infrastructure disturbance, and succession in hypoxic areas).
b Better understand spatial dynamics and relationships to different stressor/pressures (including characterization in embayments).
c Additional measurements of biomass, productivity, and community composition are needed for incorporation into food web models.

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species, fishing pressure, temperature, habitat alternation need to be better understood.

3 Cross-cutting issues:

a Remineralization of organic carbon and nitrification of ammonium from sewage treatment plant discharges can contribute to hypoxia, but direct measurements using 15N tracer and other methods will be needed to assess their importance.
b Food web dynamics are relatively poorly known; need to better understand trophic linkages between primary production and apex predators.
c Need to better understand the consequences of changes in climate affecting timing and fate of primary production.

Fig. 7.6 (continued)

Embrace sustainability. The modern environmental movement has been successful in decoupling the rise in population and economic output from similar rates of increase in the generation of air and water pollution. Increases in population and the economy over the past 30–40 years have been accompanied by slower rates of increase or an overall decrease in many air and water pollutants from regulated sources, mainly through application of pollution control technologies and product bans. But environmental problems remain, caused by more diffuse, unregulated sources of pollution and from landscape changes.

Sustainable development, definedas “meeting the needs of the present without compromising the ability of future generations to meet their own needs,”

Physical Oceanography
- Additional attention should be paid to developing assimilative models that incorporate hydrography and circulation. Better wind, river and ocean boundary data are necessary components.

Geochemistry
- CLIS and embayments will be sensitive to changes in the overall system (including climate change) and should be emphasized for monitoring/studies of carbon organic content and inputs, redox oscillations, benthos, sediment accumulation and bacterial biomass.

Pollution
- Need to characterize regulatory effectiveness by continuing periodic sampling of sediments for xenobiotics, toxicity, and benthic condition (e.g., NCA).
- Monitor sediment loads as part of a sediment management program to alleviate dredging demands
- Continue to evaluate management effectiveness by monitoring nutrient inputs and evaluating flow-normalized trends.

Ecology/Biology
- Continue to monitor the spatial and temporal variability of seagrass.
- Monitor components of the biological community, e.g. seaweeds, benthic animals.
- Improved ecosystem modeling is needed to help relate trends in harvest and survey abundances to the biology of natural resources.

Fig. 7.7 Monitoring and modeling needs to support management

1. Embrace sustainability
2. Prioritize management of existing pollution sources and impairments
3. Establish baselines of historical condition and magnitudes of change
4. Integrate climate change across programs
5. Enhance positive feedback loops
6. Improve eutrophication and ecological modeling and monitoring
7. Design adaptive management framework
8. Conduct marine spatial planning
9. Improve data management and interpretation
10. Reconnect people to the Sound.

Fig. 7.8 Recommendations to enhance EBM of Long Island Sound

(Bruntland 1987) can maintain ecosystem services while providing for other societal needs. Sustainability might strike some as out of place leading the list of science and management actions for LIS. But managing aquatic ecosystems requires a combined watershed and waterbody perspective. As the costs of mandating remediation of past environmental sins often are steep and the timeframes long, it is appropriate to start with actions that can have the most benefitrelative to cost. Development of technological infrastructure and implementation of pollutant-control regulation are usually reactions to environmental problems that exist already. Their implementation typically is three to four decades late.

Practices to develop in a sustainable manner can be accomplished with more modest upfront costs compared to remediating impaired watersheds, thus reducing the long-term costs to society. For example, low impact development can maintain predevelopment hydrology, greatly reducing stormwater, and flooding concerns and at much lower costs than post-development treatment practices (Clausen 2007; Dietz and Clausen 2008). The cost of conservation can be small compared to the cost of restoration.

Hardin (1993) advises that we must learn to "live within limits." Restoration of historical services supported by the LIS ecosystem will not be achieved if new development further adds to stressors that are a consequence of past development. This is not to suggest that the obstacles to sustainability—technological, social, political, and economic—are trivial, or that sustainability can eliminate tradeoffs in the provisioning of ecosystem services. Developed landscapes will not function as natural landscapes. Nevertheless, development for housing and commerce will remain a desired human use of landscapes; doing so sustainably will lessen its impact on water resources and reduce the scope of post-development remediation. Although place-based ecosystem restoration programs usually will not lead or coordinate broader sustainability efforts, they can and should acknowledge, promote, and support sustainable practices and can become catalysts for change with far-reaching benefits.

Interestingly, a side effect of improving water, sediment, and habitat quality in LIS is increased pressure to redevelop areas that previously were not considered desirable locations because of hazardous waste contamination, industrial activities, odors, or debris. Redevelopment projects must be seen as opportunities to enhance sustainability, with foresight to climate change adaptation, stormwater infiltration, public access, and habitat protection.

Prioritize management of existing pollution sources and impairments. Second in priority to preventing or minimizing new impairments is systematically addressing the drivers of existing impairments. Core CWA programs to attain water quality standards through pollutant source identificationand remediation, along with habitat protection and restoration, will continue to be the backbone of efforts to restore LIS. Current federal and state programs, both national and LIS-specific, must continue to advance environmental protection. Consider that national emission control programs to attain air quality standards are vital to achieving the N TMDL for LIS. And many of the notable successes in reducing contamination from toxic substances are the consequence of national product bans and discharge control programs. Planning efforts must continue to integrate, watershed-wide, multiple sources of stress on the ecosystem—wastewater treatment plants, on-site wastewater treatment systems, stormwater runoff, combined sewer overflows, agriculture, atmospheric deposition, habitat loss and modification,and home and yard care practices—in prioritizing limited resources to remediate impairments.

Establish baselines of historical condition and magnitudes of change. As one of their "top 40 priorities for science to inform" conservation and management policy, Fleishman et al. (2011) point out that scientific,political, and policy communities have not done well in developing and committing to the creation of "reliable scientific metrics for detecting chronic long-term changes in ecosystems."

Understanding the historical (and pre-historical) condition of ecosystem functions and services helps support the development of appropriate restoration targets. These reference points, combined with assessments of current conditions and the drivers of degradation, provide the context for restoration strategies (Lotze et al. 2006). In an urban estuary like LIS, restoration to historical conditions, even if known, is most likely no longer feasible. Instead, restoration efforts will need to consider what can be accomplished practically within existing conditions and the expanded human presence (Bain et al. 2007).

For example, in 1996 the LISS established a Habitat Restoration Initiative to restore and protect 12 priority LIS habitat types that have been degraded or are under threat from development and pollution. The initiative set 10-year acre and river-mile restoration targets and has tracked progress toward their attainment. This approach has been successful where broad-brush habitat requirements can be surmised from incomplete historical accounts. The extent of historical access for diadromous fishto spawn in LIS tributaries was estimated and the difference between historic and current access estimates was then partitioned into river miles that potentially are restorable versus those that cannot be restored because of current tributary and watershed conditions. These estimates provide a stronger basis to establish targets for restoring river-mile access for shad, alewife (*Alosa pseudoharengus*), and blueback herring (*A. aestivalis*). Where quantitative or even qualitative estimates of the (pre)historical extent and condition for specifichabitats are lacking, restoration targets cannot be put in the context of actual ecosystem restoration.

Integrate climate change across programs. Section 7.6 of this chapter discusses some of the changes affecting LIS attributable to climate change, including potential changes or losses in commercially-valuable species, increased susceptibility to hypoxia, and changes in the timing and intensity of riverine discharges. These climate and environmental change signals warrant integration with existing science programs and adaptation measures. Monitoring will be needed to provide insight into the direction and rates of changes. Habitat protection and restoration programs also will need to consider storm surge and sea level rise in project planning.

Adaptation strategies for climate change often rely upon management practices that protect, simulate, or restore natural ecosystem features and functions. As a result, these strategies yield multidimensional management benefitsthat build ecosystem resilience against a range of environmental stressors. Multiple climate adaptation initiatives are underway in Connecticut and New York.The Connecticut Governor's Steering Committee on Climate Change created an Adaptation Subcommittee in accordance with the requirements of Public Act 08-98. This subcommittee is assessing the impacts of climate change on Connecticut's infrastructure, natural resources and ecological habitats, public health, and agriculture and developing recommendations for changes to programs and laws that would enable state and local government to adapt to such impacts. The New York Governor's Climate Action Council, formed through Executive Order No. 24 in 2009, developed a Climate Action Plan that includes recommendation for adaptation.

One challenge will be to develop coastal management policies and guidelines relating to where, when, and how to armor shorelines or retreat in the face of higher sea levels or more intense storm surges. Long Island Sound is developed intensively along its shoreline, and redevelopment of previously degraded industrial sites is becoming attractive for commercial or residential use. Demands for protection of property and public safety will exert enormous pressures to armor and protect low-lying coastal areas against damage from the combined effects of storm surges and sea level rise (Strauss et al. 2012; Tebaldi et al. 2012).

The question of whether to construct seawalls or other shore-protection devices to stabilize the existing shoreline is scientifically complex; implementation will be costly and contentious, socially and politically. Even now erosion is essential to feed the existing beaches and littoral drift. But, as the rates of erosion increase, do we "stand or retreat?" Who has the burden of paying for shoreline protection? Is there political will to enforce setbacks to allow for shoreline accretion and avulsion as sea level rises?

One fact is absolutely clear: coastlines and their associated features naturally adjust to rising sea levels by migrating landward. It is possible that more extensive bluff erosion will occur as a consequence of waves undercutting the bluff toe at a higher elevation. But efforts to prevent erosion often have unintended consequences, and ultimately yield to the sea in the long run. Resource managers should be conservative and keep development away from vulnerable coastal features, rather than have to expend resources to protect threatened areas in desperation.

Enhance positive feedback loops. Attempts to reverse coastal eutrophication primarily focus on reducing land-based sources of nutrients, such as fertilizer applications, WWTF dischargers, and air emissions. But as noted, historical alterations in habitat quality, food webs, and community structure in coastal systems also alter nutrient processing, thus modifying the ecosystem response to reduced nutrient loads (Duarte et al. 2009). One example of a systems approach integrates watershed load reduction programs with enhanced nutrient processing in coastal systems. This may prove to be more effective at restoring ecosystem services at less cost than load reduction programs alone, helping to arrive at cost-effective, affordable, and equitable solutions. Six areas merit particular attention.

- Enhance shellfish and macroalgae aquaculture as a means to bioextract nutrients.
- Protect and restore submerged aquatic vegetation through enhanced water quality and targeted plantings and management.
- Protect and restore wetlands, considering possible marine transgression from sea level rise.
- Protect and restore vegetated buffers along streams and coastlines.
- Restore molluscan beds, particularly for species such as oysters that create subhabitats.
- Account for integrated societal and economic benefits derived from this approach.

In addition to improving the nutrient-assimilative capacity of LIS, enhancing habitat and food web functions will benefitthe provisioning of other ecosystem services, including floodprevention, species abundance and diversity, and harvestable resources.

Improve eutrophication and ecological monitoring and modeling. Water quality monitoring programs should be maintained to support improved understanding of hypoxia, identificationof status and trends, and diagnostic analyses for management, including modeling. Mechanistic models of eutrophication in LIS have been relied upon to apply scientificknowledge to a range of specificmanagement questions relating to nutrient control (HydroQual, Inc. 1996). The Systemwide Eutrophication Model, or SWEM (HydroQual, Inc. 1999), originally developed by the New York City Department of Environmental Protection in the late 1990s, currently is being used by the LISS to evaluate alternatives for hypoxia management. A LISS-funded enhancement of the model is underway and will implement a number of recommendations for improving it (O'Donnell et al. 2010a), including:

- Transition to a community modeling framework that provides open source access to SWEM to facilitate external assessment and enhancement of the model.
- Foster model collaborations, including nesting of nearshore areas and embayments within SWEM to better resolve lateral circulation and exchange.
- Link SWEM to watershed and groundwater models to better refinenutrient and water budgets.
- Modify and use SWEM to evaluate nutrient bioextraction by aquaculture of filter feeding shellfishand seaweeds (especially the warm-temperate rhodophytes such as graceful red weed and the cool-temperate kelp species).
- Evaluate strategies to improve modeled hydrographic fieldsand circulation using existing monitoring data and improve eutrophication assessments of the Sound.

Models can provide insight into ecosystem processes, but they must be used conservatively; they are only as good as the assumptions and the data that feed them. Given the uncertainties of any particular model (boundary conditions, mixing coefficients,etc.), employing a suite of models to analyze situations and make management decisions would enhance management skill over relying solely on one.

Effective modeling requires a high level of sophistication that links atmospheric deposition models with watershed and estuarine models. Successful integration must be supported by intensive monitoring of all media and research into ecosystem structure and function that verify model accuracy and predictive capability through biological endpoints. Future development of ecological models to relate physical and biogeochemical processes and energy transfer from source through higher trophic levels, including fish production, also is desirable.

Monitoring of LIS could be strengthened, including: water column carbon biomass, rates of production/respiration, and remineralization of organic matter within the water column and from the sediments of WLIS that resupplies N and P. Adding redundant buoy instrumentation would minimize data gaps in temporal coverage. Increased monitoring and study of CLIS and LIS's bays can provide sentinel insight into how LIS responds to complex interactions between nutrient control programs and changing drivers mediated through climate change. The CLIS is a transitional basin between the more divergent conditions present in

WLIS and ELIS, and responses there may be more easily detected and diagnostic of forcing variables. Likewise, the embayments of LIS are the most intensively used portions of the waterbody, and often have strong constituencies advocating for their protection. They provide enhanced opportunities to involve a community directly in resource protection. Both CLIS and LIS's embayments should be priorities for monitoring and study, and citizen involvement in structured and quality assured data collection can stretch limited financialresources. Research funded by the LISS (Vaudrey and Yarish 2010) comparing the status of eight embayments will provide a cross-system comparison and a base line for future study. This work can be supported by local community organizations, often with the assistance of volunteers.

Design an adaptive management framework. The uncertainties associated with eutrophication in LIS warrant an adaptive management approach. Successful application, however, will require a commitment from LISS partners, particularly federal and state regulatory agencies, to understand and incorporate its principals. Research and monitoring priorities must explicitly address uncertainties relevant to decision making and be designed to test cause-and-effect relationships necessary to instruct the adaptive process. Flexibility within a phased TMDL is essential to support innovation, testing, and evaluation. So is incorporation of actions within a systems approach to meeting ecosystem objectives while supporting related socioeconomic goals and outcomes as well.

Conduct coastal marine spatial planning (CMSP). Long Island Sound could derive particular benefitfrom CMSP because of the characteristics that differentiate it, both from other planning sub-regions and within the Northeast and Mid-Atlantic regions. CMSP provides an opportunity to enhance EBM benefitsbecause of its nexus to a socioeconomic context. Although a single estuary and ecosystem, LIS is administratively divided not just between two states, but between two ocean planning regions. As an estuarine sub-region surrounded by a large, urban population, and hosting intense human uses, it presents a different set of resource, use, and governance issues than regional-scale ocean management. For example, planning would be driven less by offshore renewable energy needs than by the need to manage a crossroads of energy and telecommunications infrastructure such as cables and pipelines overlaid on a historic maritime-transportation network and placed within a defined estuarine ecosystem.

Coastal and marine spatial planning for LIS will need to address conflictsarising from proposals for energy-related infrastructure proactively, including but not limited to liquid natural gas platforms, cable crossings, tidal energy turbines, etc. These efforts also will be relevant to EBM and stewardship of marine resources, including issues such as adaptation to climate change (sea level rise and coastal hazards, alterations in food webs, shifts in high-value living resources, acidification),allocation of areas for aquaculture, as well as planning for dredged material management.

An opportunity exists with the establishment of a LIS research and restoration fund (Cable Fund) established by a settlement agreement regarding two electrical cable crossings of LIS. The Cable Fund is targeting research that improves scientificunderstanding of the seafloorenvironment, emphasizing seafloormapping, in order to prevent or mitigate the effects of current or potential energy-related infrastructure or other uses. To accomplish this goal, cooperative partnerships must be formed to marry management needs with the proper data collection, management, and interpretation, with an emphasis on mapping the bathymetry and surficial geology of the seafloorin LIS to help increase the understanding of seafloorhabitats and improve resource management.

Improve data management and interpretation. Data sets that can support spatially-driven environmental assessments are proliferating. Available data, however, often are housed in multiple locations and in differing formats, making integrative assessments and gap identificationtime consuming and expensive. Specific expertise, software, or equipment is often required to support analyses. A useful step would be to complete a GIS needs assessment to identify existing and needed data, user-groups creating, housing, and using GIS data, and data products and resources needed to meet data-assessment objectives. Further, the assessment should outline the key data sets that are available and make recommendations on how to increase public access and best support future environmental assessments.

Management and interpretation of time-series water quality data must be given a high priority. All agency and university observing system data should be readily available to facilitate analyses and distribution to other users. Local embayment monitoring programs should be integrated with the other data sets to assist in planning, quality assurance, and analysis.

Improved spatial data sharing could be achieved through regional efforts. For example, an EcoSpatial Information Database (ESID) currently is being developed for the North- Mid- and South-Atlantic by the Bureau of Ocean Emergency Management, Regulation, and Enforcement (within the US Department of Interior). The system is designed to accept ecological information for additional marine and coastal areas such as LIS. Likewise, the software system could be adapted into a database specificto LIS. It would also provide an excellent framework for incorporating social and economic indicators that interact with environmental goals and objectives.

Reconnect people to the Sound. Protection and restoration of LIS compete with many other public needs and quality-of-life objectives: safety and security, economic opportunity, education, and entertainment, among many. Yet, the ecosystem services that LIS and its surrounding environs provide are integral to our economy and lifestyle. There are intrinsic and highly recognizable personal values of LIS. Public uses—fishing,boating, swimming, passive recreation among others—that contribute to a sense of place and personal connection to the resource are vital to sustaining public support for its protection. The "Urban Sea," however, cannot be set aside as a reserve or returned to pristine condition; success will be definedby a LIS and watershed where human leisure and livelihoods are sustained and intertwined with a vibrant, resilient ecosystem.

Continuing to support and develop public access and use of LIS will help build and maintain a supportive LIS constituency. One obstacle to public use is a shoreline predominantly in private ownership. This is particularly applicable to urban areas. Improved environmental conditions in urban areas will increase demand for access and provide opportunities to broaden and strengthen the constituency for LIS. Maintaining safe navigational access for the boating community, while positing some environmental challenges, also is important for maintaining a maritime tradition and economy long characteristic of the "Urban Sea." Efforts must continue to develop acceptable options for managing and disposing of dredged material.

Without strong public and political support, investments to maintain and improve existing, let alone new, water infrastructure will be a challenge to sustain. Some elements of our water infrastructure, such as the pipes conveying storm water and sewage, date back hundreds of years. Although impressive for the craftsmanship with which they were constructed, time has taken a toll, resulting in leaky systems that compromise the effectiveness of nutrient and pathogen treatment. The design life of WWTFs constructed in the 1970s is approaching or has past senescence. And many on-site wastewater treatment systems in older homes do not meet current standards for public health protection. Addressing these issues are fundamental components of federal and state water quality protection programs; they pose financial and administrative challenges more than technical.

Examples of regulation and management having protected ecosystem services with benefitsto human health and the environment need to be documented and communicated. Among the examples given in this chapter, the chemical bans and use restrictions on Pb, Hg, DDT, and PCBs stand out as having markedly reduced exposures in the environment, leading to lower body burdens in LIS organisms. The resurgence of ospreys nesting along LIS is a direct result, as are lower risks to humans from cancer and other health concerns from consuming fishcaught from LIS. National pollution control programs have improved water quality in many urban areas to such a degree that surrounding land values have increased and public recreational uses are on the rise. One such example is the reopening in 2011 of 2,500 acres in Hempstead Harbor for shellfishingfor the firsttime in more than 40 years, a result of numerous water quality improvement efforts, elimination of many industrial uses around the harbor, and water quality monitoring and shellfishtissue testing. Recognition of the successes achieved to date will help affirm the benefitsto continued investments in environmental protection. Outreach efforts must expand the conversation to sectors of the public that have been less involved, considering social media and other technologies, and be science-based.

Finally, there are opportunities to redefine normal, accepted practices in a sustainability framework and instill them in our culture so that what is customary also contributes to our economy and lifestyle while protecting our ecosystem. Residential landscapes, for example, that are more compatible with our climate and water resources can encourage yard practices that cost less money and require less time than traditional yards. Sustainability practices can be adopted without added direct costs or burdens when supported with science-based information and outreach, and the potential future management savings are real and consequential. One only needs to consider the construction and remediation costs of cleaning up the singular issue of nutrient enrichment in LIS to understand that current practices on the land create an economic deficit of essential ecosystem services that is as real as the national debt, and will eventually have to be repaid with interest.

7.8 The Urban Sea Revisited

Long Island Sound is a creation of climate change since the last ice age, and subsequently evolved to its present geomorphology as a result of fluctuations of climate and human actions. Measured physical and chemical variables, as well as the biological community, have been altered by climate changes over the last century. And so we can project with considerable certainty that the Sound, its processes, and its ecological functioning will respond to future climate change regardless of the cause. This ecosystem will be quite different a half-century into the future. Species migrations and seasons of availability may shift. Sizes of individuals and stocks may change. Some species may disappear, supplanted by others. We have been slow to recognize the changes in LIS driven by climate over the past century. These changes have been subtle relative to strong inter-annual and inter-decadal signals, and to the significant consequences of anthropogenic activity—port and industrial development, dredging, hardening of the shoreline, destruction of wetlands, diversion of water courses, industrial and sewage pollution, and fishing pressure. But the impact of storm surge, exacerbated by sea level rise, will be anything but subtle, as illustrated by the devastation of Hurricane Sandy, which made landfall on October 29, 2012 in southern New Jersey. The storm surge in parts of WLIS and the New York-New Jersey Harbor rose four meters or more above mean low water, resulting in billions of dollars in damages to the region's infrastructure. We must be prepared to deal with climate change-driven shifts and manage them so that new resources may become robust and the ecosystem services we rely upon are sustained.

Sewage discharges, whether from septic systems or WWTFs, remain a threat to the Sound, and solutions warrant innovative and forward thinking. Hypoxia, harmful algal blooms, shellfish bed closures, fish consumption warnings, and swimming restrictions all are linked to sewage. Long Island's groundwater aquifer, in particular, is threatened severely by sewage and land use. Although the region has made great strides in sewage treatment and regulatory controls, there remain challenges in designing, financing, and administering acceptable advances in wastewater treatment. Water use, reclamation, and disposal can be designed in ways that will reduce impacts (e.g., composting toilets, gray water irrigation). We can ill afford to waste potable water to relocate sewage wastes, and the environmental consequences of doing so are onerous. Getting sewage out of water would be a positive step for improving the long-term integrity of LIS, and thus should be a top priority. Society needs a clean, renewable water supply.

Eliminating discharge of polluted storm water into the Sound is also a necessary long-term goal. The challenge is that of preventing offending materials from getting into urban runoff and overland flow,and preserving pre-development hydrology, with a large portion of precipitation infiltrating into the ground to recharge aquifers and provide base flowfor streams (Arnold and Gibbons 1996). To this end, stormwater management technologies should be designed to mimic natural systems, diverting the firstpolluted flushof storm water but retaining the natural flowand timing of pulses of fresh water, which are vital for the functioning of the Sound's oceanographic processes. Clean storm water recharges our coastal systems; it is this flowthat drives estuarine circulation and establishes salinity regimes important for ecological functioning.

The outlook for the future of the quality of the Sound, its waters, ecological functioning, and aesthetic pleasures is actually quite positive, particularly if we eliminate sewage pollution. Over the last three to four decades, considerable investment has been made to understand the science of the Sound and to monitor changes in numerous, quantitative metrics of Sound health. These have formed the basis for enlightened management of an extremely complex ecosystem that spans multiple political boundaries. It should remain an imperative to continue to support estuarine research and monitoring to stay abreast of critical changes in the Sound ecosystem and to understand why they are happening.

One can take pride in the many efforts being undertaken to improve the condition of the Sound. Development of public engagement has been critical in this regard. Concerted efforts to reduce discharges of polluting materials from point and nonpoint sources, create vessel no-discharge zones, protect wetlands, buffer watercourses with vegetation, and improve public access are notable achievements. The Sound has benefittedfrom the national effort to ban lead from gasoline and stop production of PCBs. And who would have ever imagined that osprey and eagles would repopulate the area as a result of banning DDT—a nation-wide action that was initiated in Suffolk County, NY.

We can reduce and ameliorate consequences of society's insults to the Sound more effectively. Green products and green development increasingly are available to lessen our ecological footprint. We can, with strategic investments, adapt to and accommodate accelerating climate change. Conservation measures, marine spatial planning, and soft, environmentally acceptable coastal engineering technologies are some of the techniques that recently have been developed or improved. Smartly applied, they can help to assure that Long Island Sound, the "Urban Sea," retains its eminence as a beautiful, productive, enjoyable place to live and work in the 21st century.

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